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AN AIRBORNE S-BAND RACON FOR ROOSTER OPERATION

Abstract

AN/APN-6, also known as BAS, is a range-coded, airborne, S-band beacon which replies on the standard beacon frequency of 3256 mc to any standard airborne radar operating in the S_A band 3300 ± 33 mc. The equipment was developed at the request of the Services for use as a "Rooster" whose function is to call friendly aircraft to an enemy objective. The requested range performance was 100 miles; however, it was found that ranges of at least 200 miles are readily achieved within the weight limitation of about 100 lb. At the time this program was terminated, about January 1, 1944, we had completed our tests with the "quick and dirty" prototype discussed in this report. This prototype contained the basic beacon components but had not yet been engineered for minimum weight and power consumption.

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SECTION I

Introduction

While the S-band beacon described in this report was designed expressly as a "Rooster", it contains a number of recent developments in beaconry which have potentialities for other applications where a long range beacon is needed. Through the use of a superheterodyne receiver and the low voltage magnetron (2J38), a better balance between receiver sensitivity and transmitter power is achieved than in the present ground beacons which employ crystal video receivers. Also noteworthy is the simplification of the antenna system though duplexing.

Late in 1943 when the trend toward X-band beaconry was imminent, an airborne beacon was designed which was readily convertible to X-band by interchanging S and X r.f. plumbing and substituting the LVX magnetron RCA-116 for the 2J38. The X-band version, known as BAX, did not come to fruition due to the termination of this program in February 1944. However in the bench tests that were made it did demonstrate capabilities equal to BAS.

The trend now in an airborne X-band beacon is toward a short range (25 mi.) beacon with emphasis on light weight and low power consumption, considerably under what can be attained with the present design. This beacon is to be designed around the new "very low" voltage magnetron (RCA-121)* and the crystal video receiver. It might be pointed out that the substitution of the VLVX tube for the LVX in the present BAX would yield a beacon of intermediate range performance (up to 100 mi.) with considerable reduction in weight and power consumption.

SECTION II

General Description of the Beacon

AN/APN-6 also known as BAS is an airborne beacon, capable of responding automatically to interrogations from standard S-band radar. It must respond to two microsecond interrogation pulses and reject one microsecond search pulses. It must be capable of receiving and transmitting signals in all directions. Accepted interrogation pulses must cause the beacon to transmit a coded output which can be used to locate and identify the beacon.

BAS is the S-band "Rooster". The tactical function of a "Rooster" is to call friendly aircraft to an enemy objective which has been discovered by a plane equipped with a beacon. The plane circles over the objective with its beacon turned on and friendly aircraft reach the objective by homing on the beacon.

*New designation 2J41

The sequence of events taking place from the time a pulse is received until coded signals are transmitted can be shown with the aid of the block diagram figure (1). A received signal is picked up by the non-directional antenna and is fed into the mixer where it beats with r.f. from the local oscillator. The resulting I.F. is amplified and detected by the superheterodyne receiver with as little pulse stretching as possible.

To cover the 66 mc scatter band with a 35 mc. I.F. the local oscillator is switched alternately to two different frequencies. The signal is then fed into a discriminator circuit which passes the two microsecond interrogation pulses and rejects the one microsecond search pulses. Accepted signals are then fed into a duty cycle limiter whose acceptance level is determined by the number of interrogators. The signals are then fed into a gating circuit which forms a 200 microsecond gate for each accepted signal; this circuit therefore rejects all signals following the accepted ones by less than 200 microseconds. If this were not done strong transmitted beacon signals entering the receiver either by leakage or reflection might cause "singing". The signals are next fed into a coder circuit which presents a series of suitably spaced pips to the modulator. The modulator is triggered by these and supplies one-half microsecond negative pulses which the magnetron transmitter converts into r.f. pulses. The r.f. pulses are then fed through a single stub tuner to the antenna. The single stub tuner provides a variable reactive load on the magnetron for accurately setting the frequency. To prevent firing of the beacon transmitter by the radar which may accompany the beacon in some installations, a blanking circuit is provided which is triggered by a video signal from the radar.

SECTION III

Technical and Military Requirements

The following basic requirements are a composite of military requirements for a "Rooster" laid down by the Services at a conference on Military Characteristics of Portable Beacons held in the Radiation Laboratory May 3, 1943, and technical requirements based on tests with the Radiation Laboratory BAS electrical prototype.

1. Frequency

The beacon must respond to any standard radar in the S-band 3300 $\pm$ 33 mc and reply on a frequency of 3256 mc. The beacon frequency must be stabilized to $\pm$ 1 mc for all changes in load and for temperature changes of $\pm$ 25°C within the limits -40° to +50°C.

2. Range Performance

The line of sight range must be 100 nautical miles with a

minimum amount of fading. (See Section IV)

3. Antenna

The antenna must be non-directional in azimuth and have as large a beam width in elevation as practical to allow beacon operation when the airplane is banking. A beam width of at least 45° is desirable. The antenna must be as small as possible and stream-lined to minimize drag on the airplane. See Section (VII-1)

4. Discrimination

The beacon must accept all interrogation pulses greater than 2.0 microseconds and reject all one microsecond search pulses. To keep the circle of acceptance for search pulses small, pulse stretching in the receiver must be minimized. See Sections (VI, VII-4)

5. Coding

A range code must be provided consisting of two, three or four pulses, permitting a selection of eleven codes. The spacing between the successive pulses must be 12-15 microseconds for the short intervals and 35-45 microseconds for the long intervals; long and short intervals and number of pulses to be adjustable at will from a remote control box. See Section (VII-7)

6. Distress Signal

A distress signal which is not one of the code combinations is desired. See Section (VII-7a)

7. An aural monitor must be provided for monitoring the output of the receiver and the discriminator. See Section (VII-5)

8. A "blanking" circuit must be provided to render the beacon insensitive to the "main bang" of the radar which may accompany the beacon in some installations. See Section (VII-6)

9. Controls

All controls for turning on the beacon power, selecting the code, switching on the distress signal, and aurally monitoring the beacon must be contained in a remote control box which may be as much as twenty feet from the beacon. See Section (VII-11)

10. Traffic Handling Capacity

The maximum duty cycle performance is fixed by the tactical requirements. It is assumed that when the beacon is functioning as a "Rooster", the traffic will be small since not

δr is the range and h'_R and h'_B are the respective altitudes of the radar and the beacon above a plane surface tangent to the point on the earth where the "water" ray is optically reflected. For a flat earth h'_R and h'_B would be the true altitudes. For example if both planes are flying at 10,000 ft. and are separated 88 nautical miles δr = 600 ft; if they are separated 176 nautical miles at the same altitude δr = 3 mi. Since the null separation depends on r^2, the nulls are unobjectionable at short ranges, say less than 50 miles, even at low altitudes. In the extreme case of high flying craft at short range, only the direct ray need, of course, be considered. A sacrifice in range performance is to be expected near the horizon; i.e., for $r \gg \frac{h'_R \; h'_B}{\lambda}$. At this point

the power is attenuated according to the inverse fourth power of the range. Thus it is clear that for ranges under 100 miles and reasonably high altitudes the nulls are too close together to be objectionable.

1. Receiver Sensitivity

For any radar, the beacon receiver sensitivity and transmitter power necessary to overcome the inverse square attenuation and null loss can be calculated from elementary principles. Values for the receiver sensitivity° for reliable operation with ASG radar are given in Table (I). S is defined as the receiver sensitivity necessary to give a tangential signal (3 times noise) at the receiver output at the half power points of both the radar and beacon antennas. The peak power of the ASG-3 radar is taken equal to 25 KW, and the radar and beacon antenna gains are taken equal to 300 and 3 respectively.

Table I

nautical miles	depth of nulls in db	S (receiver sensitivity watts)
50	0	1.2×10^{-8}
100	0	2.9×10^{-9}
100	10	2.9×10^{-10}
200	0	0.7×10^{-9}
200	10	0.7×10^{-10}

For complete suppression of "nulls" a receiver sensitivity of 2.9×10^{-10} watts is needed. For a partial suppression of "nulls" the value must lie between 2.9×10^{-10} and 2.9×10^{-9} watts. This requirement demands a superheterodyne receiver. The sensitivity of the superheterodyne receiver employed in BAS is

5×10^{-10} watts, sufficient for ranges up to about 200 miles.

2. Transmitter Power

In calculating the beacon transmitter power, the radar T.R. loss must be added to the inverse square attenuation and "null" effect. This loss arises from the "off-frequency" operation of the beacon. For example with a radar operating at 3333 mc, a beacon pulse of 3256 mc takes a 20-30 db loss in getting through the T.R. Values for the transmitter power for reliable operation with ASG are given in Table (II). P is the peak power in watts required to give a signal equal to noise on a radar at the half power points of both the radar and beacon antennas. The radar receiver sensitivity (noise level) is taken equal to 5×10^{-13} watts.

Table II

nautical miles	depth of nulls db	T.R. loss db	P (transmitter power peak watts.)
50	0	0	.36
	0	20	36.00
100	0	0	1.44
	0	20	144.00
	10	20	1440.00
200	0	0	6.00
	0	20	600.00
	10	20	6000.00

From Table (II) for reliable operation at 100 miles the peak power should be about 1.5 KW. The peak power of the prototype is 3 KW so operation to about 200 miles is expected but with some nulls. They should be unobjectionable at altitudes considerably above the horizon even for large T.R. loss.

SECTION V

Traffic Handling Capacity

The normal function of a beacon is to reply to two micro-second interrogation pulses from scanning radars operating at about 400 p.p.s. Actually it is ofttimes searchlighted by nearby search radars with repetition rates up to 2000 p.p.s. This is especially true for ground beacons located at airports where the distances involved are so small that the discriminator fails to exclude all the unwanted traffic. In its normal function of replying to scanning radars the traffic handling capacity, in terms of the number of aircraft served, is very high even for a low average beacon duty cycle as will presently be shown. But in the event of indiscriminate searchlighting the capacity is enormously reduced. The case of the airborne beacon is simplified because it is generally far enough removed from radar systems that its discriminator excludes search pulses. Consequently the average duty cycle is low, permitting the use of smaller modulators and smaller power supplies than are ordinarily required for a ground beacon.

To determine how much traffic a beacon will handle it is necessary to consider first the effect of a number of systems searchlighting the beacon simultaneously, and next to calculate how many scanning systems on the average correspond to the number searchlighting. Since each beacon reply is followed by a 200 microsecond gate, all interrogations falling within the gates are lost. So in general the number of replies will be less than the number of interrogations by the number which are lost in the gates. The average number of interrogators receiving replies (n) for any number of searchlighting interrogators (n_o) is given in figure 2. The repetition rate of the interrogators is assumed to be 400 p.p.s. The data plotted in figure 2 are calculated for a switched receiver in which all parts of the scatter band (66 mc) are covered only half the time. (This is not quite the case for the BAS receiver because there is considerable overlapping of the regions served by the switched local oscillator; however in a receiver designed expressly for S-band coverage, the case considered here would be closely approximated. See Section VII-3 for details on the receiver) The curve n^1 is calculated for equal numbers of radars in each band (l.o. position (1) and l.o. position (2)) and curve n_2 is calculated for the case where all radars lie in one band (say l.o. position (1)). For any arbitrary distribution of radars over the band the number n will lie between these two extremes. For large value of n_o, n_1 approaches 25 and n_2 approaches 12½ corresponding to one reply for each 200 microsecond interval. For a 4 pip code with ½ microsecond pulses the maximum attainable duty cycle is 1.0% but may be as low as .5% depending on the distribution of radars over the band.

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From figure 2, for some intermediate value, say $n_o = 10$, the average number of replies lies between 6 and 7.5, corresponding to an average duty cycle of .3%. A duty cycle of 1.0% is unnecessarily large from a tactical standpoint; in addition the demands upon the size and power consumption of the modulator and power supply for this duty cycle are prohibitive for an airborne set.

The average duty cycle for an equal number of <u>scanning</u> radars will in general be reduced, because the beacon is then interrogated only within the beam width of each radar. The beam width effective in interrogating the beacon may, however, vary over wide limits - from 360° at close range to 0° in a null or at extreme range. Since the effective beam width depends on so many factors; namely, distance, nulls, radar power, and beacon receiver sensitivity, it is impossible to determine an average value to cover all conditions of operation. A fairly representative condition is one where the beacon is interrogated on the average by the full beam width of the radar, which is about 30° for ASG-3. 15° On this assumption the traffic capacity is scaled up by a factor of 24 for spinners randomly distributed in azimuth. Thus an average duty cycle of .2% would result from 144 scanners, and .3% from 240 scanners. It is presumed that the number of radar equipped planes in a "Rooster" operation would be less than either o of these two cases.

Actually the number of spinners directed toward the beacon is subject to large fluctuations which will at times push the duty cycle up to the maximum of 1%. To prevent this, and realizing that 1% is unnecessarily large from a tactical standpoint, the duty cycle has been limited to some arbitrary value (.4% in BAS prototype). With this addition the reply curves flatten off as shown in Figure (2).

Another factor which limits the traffic handling capacity is the time allotted to one searchlighter. This time becomes smaller as the number of interrogators grow. If there is only one, it will receive 50% reply, because a switched receiver is employed. The permissible number is fixed by the least response necessary to give a clear indication on the radar's indicator - this is arbitrarily taken to be about 30%. In figure (2) is shown the percent reply R to one interrogator as a function of n_o for D.C.L. adjusted to .4%. Two cases corresponding to n_1 and n_2 are given. From figure 2, for 30% minimum response the maximum number searchlighting the beacon should not exceed 10, or the number scanning about 240.

The average response to an interrogator might be expected to be subject to large fluctuaions. For example, if all searchlighters had exactly the same repetition rate, the configuration established in the first 2500 microsecond interval would be maintained and some systems would receive full reply and others none. Fortunately, the repetition rates are distributed over a interval of about 400 ± 10%, so one can reasonably expect enough reshuffeling in about a second to give average values which do not depart much from values given in figure 2. For scanning radars there is added reshuffeling due to the various scanning rates.

A severe test of the D.C.L. was given the BAS prototype when it was tested as a ground beacon at Deer Island with the ASG radar. Although the discriminator was adjusted to exclude 1 microsecond pulses, the circle of confusion (see Section (VI)) for strong 1 microsecond pulses from East Boston Airport included Deer Island. With a random searchlighting and scanning by 400 and 2000 p.p.s. radars the duty cycle was maintained continuously at .4%. Under these conditions the beacon was followed out to 115 nautical miles with a clear P.P.I. display, and with no more fading than is attributable to "nulls".

SECTION VI

Circle of Confusion - Discrimination

The specifications for BAS call for pulse width discrimination[2]. In this type of discrimination the beacon replies to 2 microsecond interrogation pulses but rejects 1 microsecond search pulses. The main function of the discrimination is to decrease the average duty cycle of the beacon. However, it is also a security measure in that the beacon is not wantonly interrogated by search radars--the enemy could determine azimuth from such interrogations.

The "circle of confusion" is defined by the radius within which one microsecond search pulses will trip the beacon. A discrimination limit is fixed by the point where strong one microsecond search pulses appear as two microsecond pulses due to pulse stretching in the receiver. The degree of discrimination can be defined as the difference in r.f. power levels of a tangential° two microsecond pulse and a one microsecond pulse strong enough to fire a discriminator adjusted to accept the weak twos. The discrimination of BAS, defined in this manner is about 60 db. The circle of confusion d for a peak radar power P and gain G_R can be calculated from the equation

$$d = \frac{\lambda}{4\pi}\sqrt{\frac{PG_R\ G_B}{D.S}}$$

where G_B is the beacon antenna gain, S is the beacon receiver sensitivity and D is the discrimination as defined above. For example for operation with ASG; P = 25 KW, $G_R = 300$, $G_B = 3$, S = 5×10^{-10} watts and D = 10^6 (60 db), the circle of confusion is 0.85 n.miles. The measured circle of confusion was 2 miles for solid firing. The discrepancy between this value and the theoretical value is undoubtedly due to a higher receiver sensitivity in the experimental model. See Section (IX).

° This is a signal 3 times noise (r.m.s.)

Components

1. The Antenna

Many demands are imposed upon an antenna system which will satisfy the technical and military requirements outlined in Section (III). A design which gives horizontal polarization, complete coverage in azimuth and a large vertical beam width, is the stacked dipole antenna shown in figure (3). For this antenna, with the dipoles spaced one-half wavelength, the gain is approximately equal to the number of elements N, and the vertical beam width to one-half power is $\frac{120}{N}$. The broad beam, at least 40° to half power, and small antenna size to reduce drag are consistent, but impose limitations on the antenna gain--which must then be less than three. In practice it is difficult to realize the free space beam width without mounting the antenna far from the airplane. In general it is to be expected that the beam width, and consequently the gain, will vary with azimuth in an unpredictable manner depending on the physical surroundings, disposition of wings, etc.

To minimize the size of the antenna, duplexing is employed, i.e., a single antenna serves both for receiving and transmitting. The single antenna can be made broad band to cover the necessary range 3256-3333 mc with a standing wave ratio in power not exceeding 1.7 anywhere in the band.

A number of antennas of gains, 2, 3, and 6 were tried. They were mounted on the under side of an AT11 and could be raised or lowered to determine the requisite distance from the airplane. See figure 4. While insufficient tests were made to determine the best gain and distance, it was found that a 3 dipole antenna mounted at least 12 in. from the fuselage to the first dipole gave good results. With this arrangement the beacon could be interrogated when the airplane was in a 20° bank turning away from the radar, but was lost when it banked toward the radar due to the shadow cast by the wings.

2. Duplexer-Mixer

A GL446 in a special radial cavity is used both for duplexing and mixing. A drawing of the cavity is shown in Figure 5 and a photograph in figure 6.

The operation of the cavity as a duplexer can be understood from Figure (7). The T-junction is an odd number of quarter wavelengths from the cathode of the GL446, with about one quarter wavelength of this between the cathode and a point on the grid just inside the glass of the tube. The magnetron is effectively an integral number of half wavelengths from the T-junction. For received signals, the cavity presents a low impedance and the magnetron presents a high impedance at the T-junction; consequently, the

antenna sees a low impedance looking into the cavity. For the strong transmitted signals, the GL446 draws grid current, so the magnetron sees a high impedance looking into the cavity. An estimated loss in received power which can be attributed to duplexing is less than 2 db; and the loss of transmitted power into the cavity is about 1 db.

Mixing takes place in the cathode-grid cavity as shown in Figure (7). The signal input which occurs half way out on the radius of the cavity is at a position of voltage maximum, and the local oscillator which is a bit further out on the radius, is down about one third of the voltage maximum. The I.F. is taken off the plate of the GL446. The local oscillator excitation, supplied by a 2K28 (McNally) is about 20 mw. The noise figure of the cavity varies from 20 db above KTΔF at midband, 3300 mc, to 23-25 db at extreme ends of the scatter band.

The Q of the cavity is less than 10 due to tight coupling and electron loading. No silver plating is necessary, and a soldered construction is permitted. Tuning is accomplished with a single screw and should be done while the magnetron is on, since the tube behavior may be affected by the magnetron power.

At first sight it appears that a tube mixer would give an unwarrented loss in receiver sensitivity over what one might get, for example, with a broad-banded T.R. box and a crystal mixer. However it happens that the noise figure of the first stage of the 35 mc I.F. competes with the noise figure of the tube mixer. So even with a crystal the first I.F. would still determine the noise level. In addition, the tube mixer has a conversion gain of about 10 db, requiring less gain in the I.F. stages than would be required for a crystal mixer.

3. BAS Receiver

The scatterband of magnetron frequencies on the S-band has been specified as 66 mc. centered on 3300 mc., so that the receiver, in order to cover this band in spite of momentary drifts and inaccuracy of adjustment, must be designed to repond over a slightly larger range of frequencies, a minimum of 70 or 75 mc. The receiver must also present to the discriminator a pulse which retains its shape over as wide a range of input power as possible, so that a system using 1 microsecond search signals at a relatively short distance from the beacon will not trigger it by appearing as a 2 microsecond beacon interrogating signal. It is very desirable to be able to use one antenna for transmitter and receiver for space and weight requirements and also for ease of placing the antenna on the plane. See figures 6 and 13 for views of r.f. plumbing and receiver strip.

For a working range of 100 miles, the choice of superheterodyne as opposed to crystal video was indicated. See section (IV-1). Although at least two possible means of covering the required bandwidth specified above were available, for purposes of

interchangeability between S and S-band beacons, the receiver for BAS was made to cover about 110 mc., which is the coverage required on X-band, and obviously more than enough for the S-band.

By means of electronically switching the frequency of the local oscillator between two points correctly selected, the 110 mc. is covered with an i.f. bandwidth of 35 mc., properly centered, as shown in the figure (8).

Thus the receiver covers the whole band in four "sidebands", and as long as the switching rate is less than half the minimum repetition rate of the interrogating signals, the beacon will respond to an interrogating system about half the time.

The use of a single antenna for receiver and transmitter, which obviously has great advantages in an airborne system, was made possible by the use of tube mixer, which is discussed in detail in Section VII-2. Although the GL446B tube mixer gives a noise figure for the receiver which is worse than a crystal mixer, theoretical data showed that sensitivity would still be considerably above that required (10^{-9} watts).

The fact that the local oscillator was to be switched between two frequencies which were necessarily quite critical required the accurate measurement of these frequencies, and also required a rough check on whether the local oscillator was putting out about equal power at the two frequencies. A single S-band cavity was used for this purpose after being modified to allow it to be set mechanically at the two specified frequencies and also at a point approximately midway between these frequencies. A secondary coupling loop in the l.o. cavity was used to couple power to the wavemeter.

Figure 9 shows the circuit used to switch the l.o. frequency. The functions of the various controls and the resulting wave-shape of the output are as follows:

> The switch is ganged with the 50K pot., so that turning the pot all the way down opens the switch. The output lead, a tap on the 50K pot., is connected to the l.o. reflector, which draws practically no current; therefore, when the switch is open, the reflector will be at a d.c. level controlled by the 25K pot as shown in Fig. 10A. When the switch is closed, the 6J6 multivibrator puts out a rough square wave (Figure 10b) of about 150 c.p.s. repetition rate; the 6AK5 cathode follower acts to clip the top and bottom of this square wave, giving the wave shape shown in Fig. 10C. It is seen that the more negative level of the square wave is still that originally set with the 25K pot. Therefore the level set with the 25K pot. is independent of the adjustment of the 50K pot., although the reverse is not true.

The i.f. amplifier shown in Fig. 11 uses seven stages of 6AK5's in a circuit known as "shunt-series peaking".[3] It gives an

overall i.f. gain of about 85 d.b., and a pass-band extending from about 10 to 45 mc. Essentially, the interstage coupling circuit is a video-type circuit which is simply extended to give a band-pass of a few kilocycles to 45 mc. In order to prevent the i.f. pass-band from overlapping into the actual video pass-band of the order of two mc., a filter is introduced into each cathode, which results in sharp degeneration for frequencies below 10 mc. Thus an actual i.f. amplifier results, and in spite of the loss of the first 10 mc. of the possible pass-band, the advantage of this type of circuit over any other type now known is still large. Theoretically, the resulting pass-band should be perfectly flat, but actually, the curve is more like that shown in Figure 12.

The fact that there is an actual variation of 4 to 6 db. gain over the band is not objectionable, since sensitivity is still more than enough at the lowest point. Although the i.f. pass-band, because of its shape, probably does introduce ringing on a 1 microsecond pulse, this ringing is at a very high frequency, and never gets through the narrow-band video which follows the second detector.

Since, in order to bring the noise up to the desired 10 or 15 volts, and obtain the best sensitivity possible from the receiver, an overall receiver gain of perhaps 130 db. is required (not counting the loss in the second detector), the video must provide about 50 db. of gain, and a bandwidth sufficient to preserve the shape of the pulse over wide ranges of amplitude out of the second detector. (See Fig. 11 for circuit diagram of video amplifier). In other words, the video must not "stretch" the pulse for large signals. This "stretching" phenomenon and the various possible ways of overcoming it are described in detail by M. F. Crouch[4]. The video circuit is fairly conventional except in the use of a small coupling condenser in the output stage, which greatly reduces microphonics, and also introduces a large, but reasonably short overshoot. There is also no provision for a power output stage, so that care has been taken not to load down the output of the receiver with any cable or unnecessary stray capacitance. The resulting "stretching" characteristics of the receiver seemed fairly satisfactory in bench tests, about 60 db. between minimum 2 sec. signal and maximum 1 microsecond signal which would not trip the beacon. This discrimination factor depends greatly on the discriminator circuit and particularly how the receiver is coupled into the discriminator.

4. Discriminator

The function of the discriminator is to reject 1 microsecond search pulses and accept two microsecond interrogation pulses[2]. (For a discussion of the tactical need for discrimination, and definition of terms see Section (VI). A circuit diagram of the discriminator is shown in Fig. 14 and a block diagram with wave forms is shown in Figure 15.

The basic circuit component in pulse width discrimination, as employed in BAS, is the integrator V1. In this stage a negative

pulse from the receiver renders the tube non-conducting, provided the amplitude of the input signal is equal to or greater than E_{min}, the amplitude required to drive the tube to cut-off. A "drooling" pulse is then formed at the plate whose amplitude is proportional to the pulse width for amplitudes greater than E_{min}, and whose slope, essentially constant for the small times involved, is determined by the RC time constant. The wave form at the plate of V1 is shown in Figure 15. The constants of the integrator stage are selected so that E_{min} is about two or three times noise at the output of the receiver. The bias on the amplifier V2 following the integrator stage is adjusted so that it conducts for signals whose duration is two microseconds or longer and whose amplitude is equal to or greater than E_{min}. The negative pulse from the output of the biased amplifier triggers the one-shot multivibrator V3. On the output of V3 a negative gate is formed whose amplitude is independent of the strength of the beacon interrogating signal. This output pulse is fed to the duty cycle limiter (D.C.L.) stage in the coder. To increase the degree of discrimination, stretch-amplitude-compensation has been added. This is indicated in Fig. 15 by the dotted line around V_1. An amount of "feed forward" through the .01μf condenser (Figure 14) is provided which is proportional to the amplitude of the receiver output. The stretch compensation is due to the decrease in the "drooler" amplitude for strong pulses. It is important to note that the output pulse from the multivibrator stage is delayed in time from the received signal by two microseconds. This delay is inherent in this type of discriminator which waits two microseconds before deciding to accept a pulse.

The setting of the bias on the amplifier stage V_2 determines whether an output is obtained from the multivibrator V_3. The normal set-up procedure is to adjust the bias on V_2 so that the multivibrator trips about 50% of the time for a two microsecond signal of amplitude E_{min} at the input to the integrator stage. This partial firing of the multivibrator for input signals of amplitude equal to E_{min} is due to the noise which exists on the integrated pulse. (See Fig. 15 for the wave forms).

From the bench tests which were made on the BAS receiver and discriminator, discrimination of 50 db was obtained without stretch compensation. This meant that a one microsecond signal 50 db stronger than a two microsecond signal of amplitude E_{min} would trip the discriminator. It should be noted that the receiver stretched the one microsecond signal to two microseconds at the 50 db point. By using the scheme of stretch-amplitude-compensation it was possible to increase the discrimination to 60 db. In a number of field tests the "circle of confusion" was found to be about 2 miles.

5. Aural Monitor

One of the tactical requirements of BAS is an aural monitor which enables the beacon operator to listen for radar signals with the beacon transmitter turned off. Two monitoring points are provided: one on the output of the receiver which accepts

all radar interrogations, and one on the output of the discriminator which accepts only beacon interrogations. Consequently the beacon operator can be in touch at all times with all radar traffic within range of the beacon, and turn on the transmitter only when beacon interrogations are present. A monitoring jack, and a transmitter switch are located on the remote control box for ready accessibility. A block diagram of the monitor circuit is shown in Fig. 15, and a circuit diagram in Fig. 14. To keep the capacity loading of the receiver as small as possible the amplifier V7 is cathode-to-cathode coupled with the integrator stage in the discriminator. The overshoot of the received signal, about 20 microseconds long, is amplified in V7 and fed through the cathode follower V8 to the earphones. In monitoring interrogation pulses, the output of the M.V. stage V3 is feed through V8 to the earphones.

Field tests show that it is possible to get an indication of the amount of radar traffic from the audio monitor system; but because of the beat notes produced by the frequency of the interrogation signal and the frequency of the receiver switching, it is impossible to identify a given plane by the pitch of the signal from the audio monitor.

6. Radar Blanker Circuit

Since a radar set may accompany the BAS in some planes, it is necessary to prevent triggering of the plane's own beacon by the radar. A 20 microsecond gate initiated by a video pulse from the radar renders the beacon insensitive to the main bang and also to strong echoes.

A block diagram of the blanker circuit is shown in Fig. 15. The operation of the circuit is as follows: A positive video pulse from the indicator central of the radar set is amplified in V4. This negative pulse triggers the multivibrator V5. Coupling from the blanker to the discriminator is done by means of the switch tube V6.

This blanker circuit has been bench tested and found to be very satisfactory. It has not been field tested because no complete beacon and radar installation has been made simultaneously in the same plane.

7. BAS Coder

The beacon response to radar interrogation must have some form of code to identify the beacon and to make it clearly discernable from radar-echo signals. For this reason the beacon response is range coded i.e., the beacon answers the interrogation with an undelayed pulse followed by a series of delayed pulses, appearing on the radar scope as a series of signals of the same azimuth, but at different ranges.

A beacon coder is essentially a circuit for generating delayed pulses; the fundamental difference between various kinds of coders lies in the type of circuit used to obtain this delay.

In the case of BAS the usual series of multivibrator delay circuits has been replaced by a series of overdriven amplifiers, because this type of coder is more adaptable to remote control of code setting. See Figure (17).

Distinguishable Codes

The BAS coder has two variables which can be controlled to obtain different codes; namely, the number of code pips, and the spacing between these code pips. The maximum number of code pips is 4, and the spacing may be either short or long. The total number of different codes available from such a coder is 15. However, this number is decreased by certain limitations placed on the code. Since a single pulse might possibly be confused with radar echoes, it is necessary for the code to have at least two pulses. Also, unless both short and long delays appear in the beacon code display on the radar scope, there may be some doubt as to whether the delays between pips are long or short in a code having equally spaced pips. Thus, two codes of the same number of pips, one having all short delays and the other all long delays, are not considered distinguishable. This reduces the number of distinguishable codes to 11.

Circuit Operation

A block diagram of the coder and waveforms are shown in Figure 16, and a circuit diagram in Figure 17. The input stage V_1, operates in conjunction with the duty cycle limiter and will be treated in Section VII-8. V_2 is a M.V. stage forming a negative gate about 200 microseconds long. This gate serves the purpose of triggering the coder, and of the protecting the coder from further triggers until the last of the delayed pulses has been transmitted. The succeeding stages V_3-(a), V_3-(b) and V_5-(a) are the delay stages; they form the three delay periods of the 4 pip code. The principle of operation of a delay stage can be described with reference to V_3-(a). Since its grid is tied to B+, the tube is normally conducting. The M.V. negative gate coupled to the tube through a differentiating condenser, turns the tube off until the condenser has discharged through the grid lead. The recovery time of this grid circuit, which determines the delay of the stage, is dependent upon the values of R and C of the circuit and upon the magnitude of the positive voltage toward which the control grid recovers. By setting this positive voltage either at 250 volts or at 60 volts, a recovery time of 12-15 microseconds or 35-45 microseconds respectively, may be had. See Figure 18. Since only a change of DC voltage is necessary to control the code delay periods, the switching of the code may be easily accomplished at a remote control box without any trouble from cable capacities. The large positive pulse with a steep lagging edge that appears at the plate of the delay stage V_3-(a) triggers a similar delay stage through another differentiating condenser. Since the delay stages have positively biased control grids, the positive part of the differentiated pulse does not affect the tube; but the negative part triggers the second delay stage. Thus, except in the first instance, each delay stage is triggered by the lagging edge of the plate pulse from the

preceding stage.

The two positive pulses from V_3-(a) and V_5-(a) are fed through a coupling circuit to the control grid of the first collector, V_5-(b). The pulse transformer in the plate circuit of this triode has a core which quickly saturates, and this causes the pulse transformer to differentiate the two 12-15 or 35-45 microsecond pulses that pass through its primary winding. The resulting four pips, alternately positive and negative, thus correspond to the leading and lagging edges of the two positive pulses from the delay stages. The two output windings of the pulse transformer are connected for different phase output and drive the two grids of a double triode in a blocking oscillator circuit V_6. The blocking oscillator acts as the second collector and provides pulses of equal amplitude to drive the cathode follower output stage, V_7.

To obtain codes of two or three pips, some electrical arrangement is necessary to remove the last pip or the last two pips. The latter is accomplished simply by removing the plate voltage from the last delay stage, V_5-(a) so that only a single positive pulse from the plate of the first delay stage reaches the grid of the first collector. V_5-(b).

In order to have a three-pip code, it is necessary to shorten the recovery time of the third delay stage V_5-(a) until its long plate pulse is reduced to a 1-2 microsecond pip. Such a pip will not be differentiated by the pulse transformer in the plate circuit of the first collector but will pass on to the second collector as a single positive pulse. Thus, a three-pip code derives the first two pips from the first delay stage, and the last pip from the third delay stage. The recovery time of the grid circuit of the third delay stage V_5-(a) is shortened by connecting the grid to the cathode of V_4 through a resistor. The plate of V_4 is grounded. When a three-pip code is desired, its grid is ground potential and the tube acts as a diode, allowing the differentiating condenser in the grid circuit of the delay stage to recover very rapidly. If a four-pip code is to be used, the grid bias of V_4 is switched 150 volts negative and it no longer affects the operation of the delay stage. It will be noted that only a change of DC voltage is necessary to control the number of pips; this can easily be accomplished by a simple switching arrangement at a rémote control box.

7a. Distress Signal

The specifications of BAS call for a distress signal--a signal which would instantly distinguish itself from the usual code display. For this reason it was not sufficient to reserve one of the codes for use as a distress signal.

A simple type of distress signal, easy to accomplish electrically, may be had merely by "jizzling" the last three code pips; i.e., by continually varying the time delay of each of the last three pips over a range of some 35 microseconds. The delay is varied by changing the DC voltage toward which the control grid of the 1st delay stage V_3-(a) recovers. A 400 cycle AC voltage from the

power transformer condenser coupled to the DC point swings the DC level over the required range. Since the other delay stages are triggered by the lagging edge of the pulse from the first delay stage, the last two code pips follow the time shifts of the second pip. The display of such a system appearing on a PPI scope consists of a single undelayed pip followed by a series of sine waves the amplitude of which is determined by the range of time delay variation. The number of cycles of sine wave appearing on the PPI depends upon the scanning speed and beam width of the interrogating radar.

8. Automatic Duty Cycle Limitation[5]

A circuit diagram of the duty cycle limiter is shown in Figure 17 and a block diagram in Figure 16. The provision for automatic duty cycle limiting consists essentially of two circuits; a circuit which develops a bias proportional to the duty cycle, and a second circuit to which this bias may be suitably applied.

The bias developing circuit is comprised of a buffer amplifier, V_8, which prevents serious loading of the coder, and a diode rectifier, V_9. The rectified pulses develop a negative bias at the diode plate which is filtered in the diode output circuit. The long time constant of this filter circuit tends to allow the beacon to give full response to momentary overloads. Proper adjustment of the constants of the circuit prevents the bias vs. duty cycle curve from flattening off at a relatively low recurrence rate and allows good potentiometer control of the duty cycle at any value from .05 per cent to 1 per cent.

This bias must be applied in such a way that at high duty cycles there will be no discrimination in favor of strong interrogating signals from nearby radars. This rules out the method of applying the bias to desensitize the receiver. The bias must be applied to some circuit in the beacon having a constant amplitude input signal; the input circuit of the coder is convenient for this purpose. A cathode follower circuit V_4-(a) is used because it is insensitive to video pickup and because it provides a negative pulse suitable for diode coupling (V_1-b) to the multivibrator gate. As the duty cycle becomes large, the duty cycle bias cuts off the cathode follower V_1-(a) and the coder cannot be triggered again until the bias goes down. A diode is used to couple the cathode follower to the coder gate circuit. When the coder gate is fired, the plate of the diode is driven negative and no trigger can get through the diode until the gate circuit recovers.

9. BAS Modulator

The BAS modulator consists of an 807 blocking oscillator tube driving two 829A amplifiers in parallel, the output of which is stepped up by a 1:2 pulse transformer and applied to the cathode of the magnetron. By using the 829's as constant current tetrodes, the modulator transmits pulses of constant amplitude for all rates of beacon interrogation up to 0.4% duty cycle and about 10% change in line voltage. See Figures 19, 20 & 21.

The 807 blocking-oscillator is triggered from the low

impedance cathode follower output which consists of a series of positive pips formed by the coder. The positive pulse of about 170 volts is coupled by means of the condensers in the delay line to the grid winding of the B.O. pulse transformer. As the grid is driven more positive than cutoff, plate current flows which induces a voltage in the grid winding such that the grid is driven more positive. At the same time a negative wave is sent down the delay line, is reflected, and returns to oppose the positive drive on the grid. The drop in plate current caused by this reflected voltage together with the tube saturation induces a negative voltage in the grid winding which quickly drives the tube past cutoff. The line constants are such as to make the length of the pulse 0.5 microseconds. The third, or output, winding on the B.O. pulse transformer inverts the negative pulse on the plate and feeds a positive pulse of 360 volts amplitude to the grids of the 829's. The 1.5 1 step-down ratio of plate to output winding gives a low impedance source to drive the low impedance load presented by the grids of the 829A's in parallel.

The ratio of voltage to current of the pulse applied to the magnetron is determined by the magnetron characteristics. A typical operating point for the 2J38 magnetron is 3 amps peak current, 5 kv peak voltage. Depending on the magnetron used, the power output will lie between the 2 kw and 4 kw.

Using the above values in a numerical example, we find that to produce such a pulse in the secondary of the pulse transformer assuming 100% efficiency the pulse in the primary of the plates of the 829A's must be 6 amps and 2.5 kv. However, the pulse transformer efficiency is about 70%, so that the peak current is more nearly 8.6 amps. For regulation the drop across the 829A's must be about 800 volts requiring 2500 + 800 = 3300 volts from the high voltage supply. For a 0.4% duty cycle the average high voltage current is $8.6 \times 10^3 \times 0.004 = 34.4$ ma. For any smaller duty cycle the applied high voltage and tube drop will be greater due to non-regulation, but the output pulse will remain quite constant.

The chief advantage in using this type of modulator is that a relatively low voltage is used on the hard tubes for producing a regulated higher-voltage pulse. The prime requisite for regulation is a regulated screen voltage, which is supplied by an 807 shunt regulator, and is variable to control the peak magnetron current and consequently the r.f. output of the 2J38.

10. Transmitter

The transmitting tube used in BAS is the 2J38 magnetron. Its average characteristics are given in Figures 22 and 23. While its power output (about 2 kw under the operating conditions of BAS) is greater than what is required for 100 mile range, it is the only low voltage S-band tube in production. Its only competitors are the GL446 and GL464 triode transmitters which give outputs under what is required for reliable operation.

The r.f. frequency is stabilized by thermostating the tube. The addition of a holding cavity appears unnecessary to achieve the required stability. The frequency is stabilized to within 1.0 mc for a .4% change in duty cycle and 25°C about any ambient temperature within the limits -40°C to +50°C.

The frequency is adjusted to beacon frequency (3256 mc) by means of a single stub tuner which provides a variable reactive load on the tube[6]. With this device any tube in the band 9.180 to 9.220 can be pulled to spot frequency.

11. Remote Control Box

A control box shown in Figure 24 is provided for remote control of the beacon. This box can be placed as much as 20 feet from the beacon. The following controls are provided:

1--on-off power switch.
2--switches for setting all code combinations.
3--visual indication of all codes.
4--aural monitor jack for ear phone.
5--aural monitor volume control.
6--on-off switch for transmitter.
7--switch for distress signal.
8--switch for connecting aural monitor to interphone system of aircraft.

The code is indicated by lamps which illuminate rectangular slits in the cover; thus if alternate slits are bright the code is 1111 (read: one, one, one, one); if the first two are bright, the next one dark, and the next two bright, the code is 22 (read: two two) etc.

SECTION VIII

A.C. and D.C. Power Requirements

In table (III) the A.C. and D.C. power requirements of the BAS prototype are tabulated for a number of duty cycles and r.f. power outputs. It might be pointed out that these requirements can be reduced by consolidating power supplies. In a beacon engineered to consume minimum power, the total power consumption can be held to 300 watts for .2% duty cycle and 2KW peak power.

Table III

Total Power (A.C. D.C.) watts for BAS

Duty Cycle %	R.F. (KW)	Total Power	Mod. Power	AC Watts	DC Watts
0	0	350	0	260	90
.05	2	360	10	270	90
.1	2	370	20	280	90
.2	2	390	40	300	90
.4	2	430	80	340	90
.2	3-5	425	75	335	90
.4	3-5	500	150	410	90

SECTION IX

Flight Tests

The flight tests were made with BAS mounted in an AT-11 as shown in the frontispiece. Both duplexed and separate antenna systems were tried. The antennas were mounted on the under side of the plane and were made retractable so that the distance from the fuselage to the antenna could be varied. A typical antenna installation is shown in Figure (4). The radars used in the tests were the DMS-1000 (installed on the top floor at East Boston) in ground-to-plane runs and the ASG-3 (installed in an AT-11) in plane-to-plane runs. One test was also made against the ASG-3 with the BAS as a ground system at Deer Island to investigate its possible use as a ground beacon.

The operating conditions of the equipments were the following: The DMS-1000 operated at 9.11 cm with 20 db T.R. loss for beacon signals, and the ASG-3 at 9.17 cm with 10 db T.R. loss. In the one plane-to-ground test the ASG-3 operated at 9.05 with about 30 db T.R. loss. The peak power of the DMS-1000 was about 25 KW and that of the ASG-3 30 KW. The radar receiver sensitivities, judging by search performance, were greater than 10^{-12} watts. The peak power of the beacon was 3 KW and the receiver sensitivity 5×10^{-10} watts. The duty cycle was limited to .4% by the duty cycle control. The flight tests of BAS are summarized in Table IV.

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FLIGHT TESTS WITH BAS

Ground	Airborne	Beacon Antenna Gain	T.R. Loss	Altitude	Range	Circle of Confusion	Comments
					n. miles	n. miles	
BAS	ASG-3	14 (BGS) Deer Is.	20 db	line of sight	115(no lmt)	13	weaker nulls than with BGS
DMS-1000	BAS	Double Antenna 2 trans. 2 in.[1] 2 recvr. 7 in.[1]	20 db 20 db	10,000	90	no check	bad nulls
DMS-1000	BAS	2 (duplexed) 12 in.[2]	20 db	8,000	115 no limit	2	bad nulls beyond 100
DMS-1000	BAS		20 db	10,000	100 no limit		
	ASG-3		10 db	6,000	170 no limit	2	plane-to-plane

1. Distance from fuselage to nearest element.

2. This distance was the minimum for satisfactory performance.

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554-22

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6. Adjustment of Magnetron Frequency by an External Tuner - F. F. Rieke, Report 412, September, 1943.

Acknowledgment

The names of those engineers who were closely associated with the development and testing of BAS are given below. The components to which they made the greatest contribution are also listed.

G. Heaton - Coder, D.C.L. and preparation of manuscript

W. Rodeback - Modulator

I. Sudman - Discriminator, D.C.L. suppressor, and plane installation

R. Dickinson - Antenna

P. Cole - Duplexer

Z. Wilchinsky - Duplexer

J. Tinlot - Receiver

L. Orpin - Flight testing

E. R. Gaerttner
March 1, 1944

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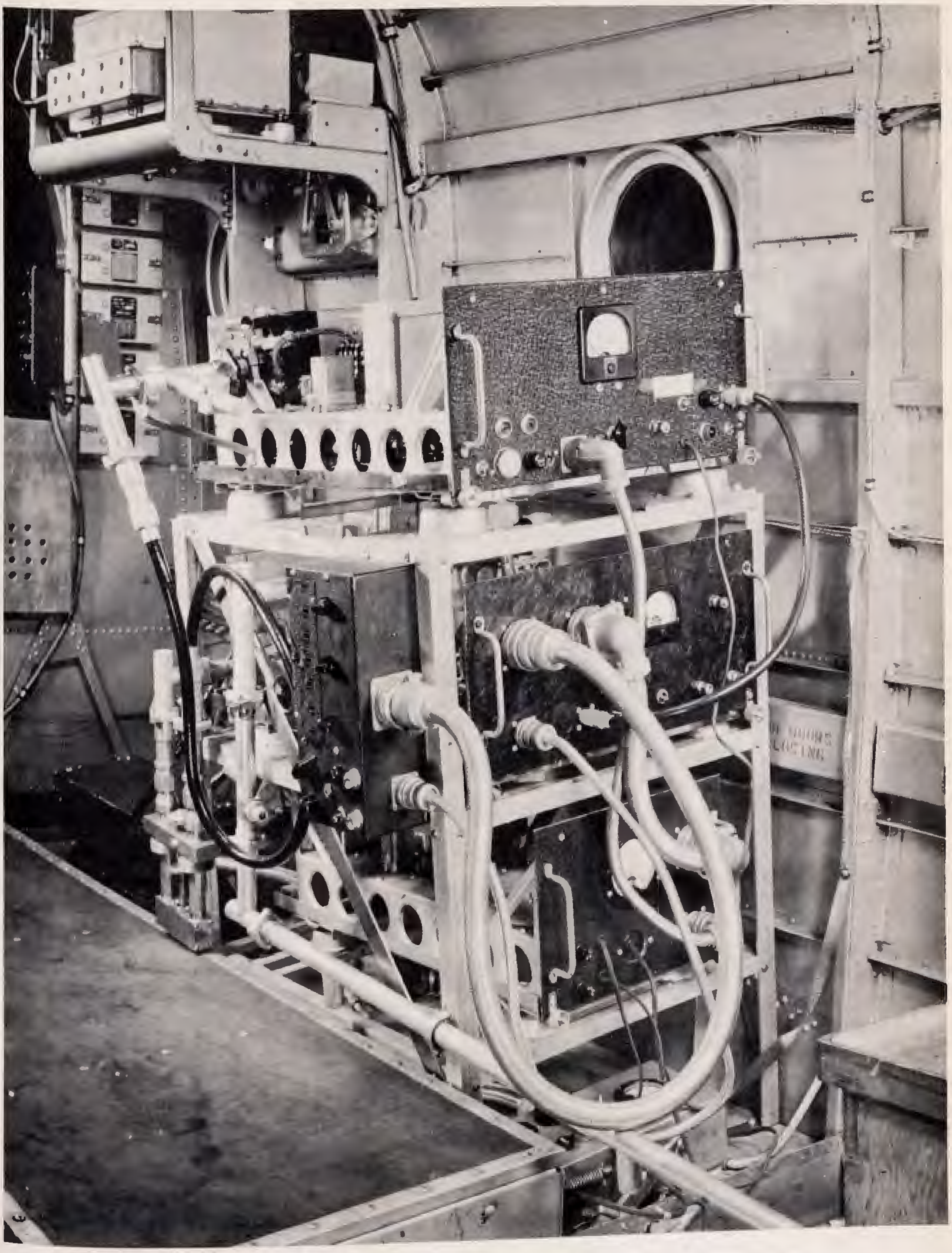

BAS IN AT-11

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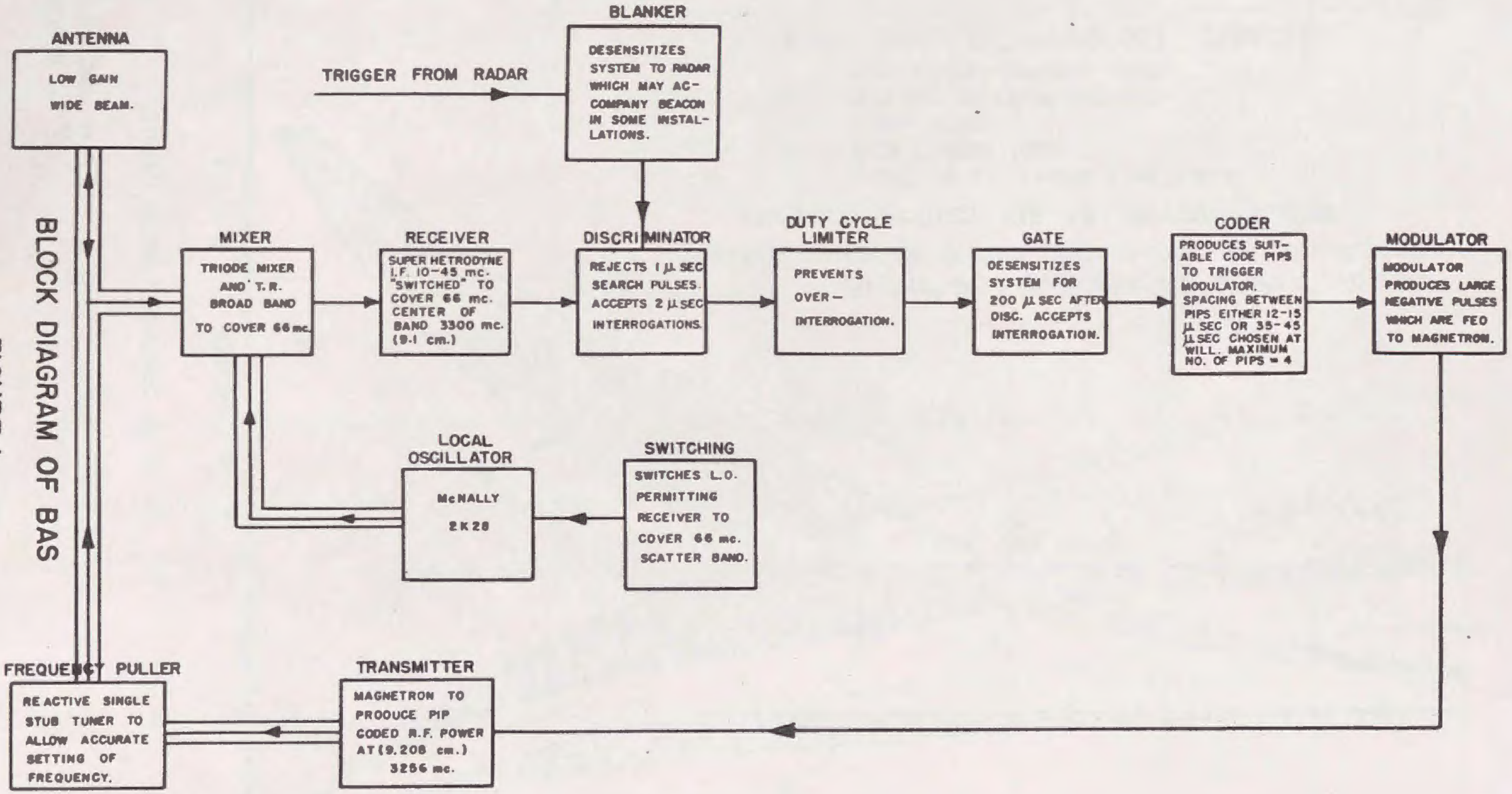

BLOCK DIAGRAM OF BAS

FIGURE I

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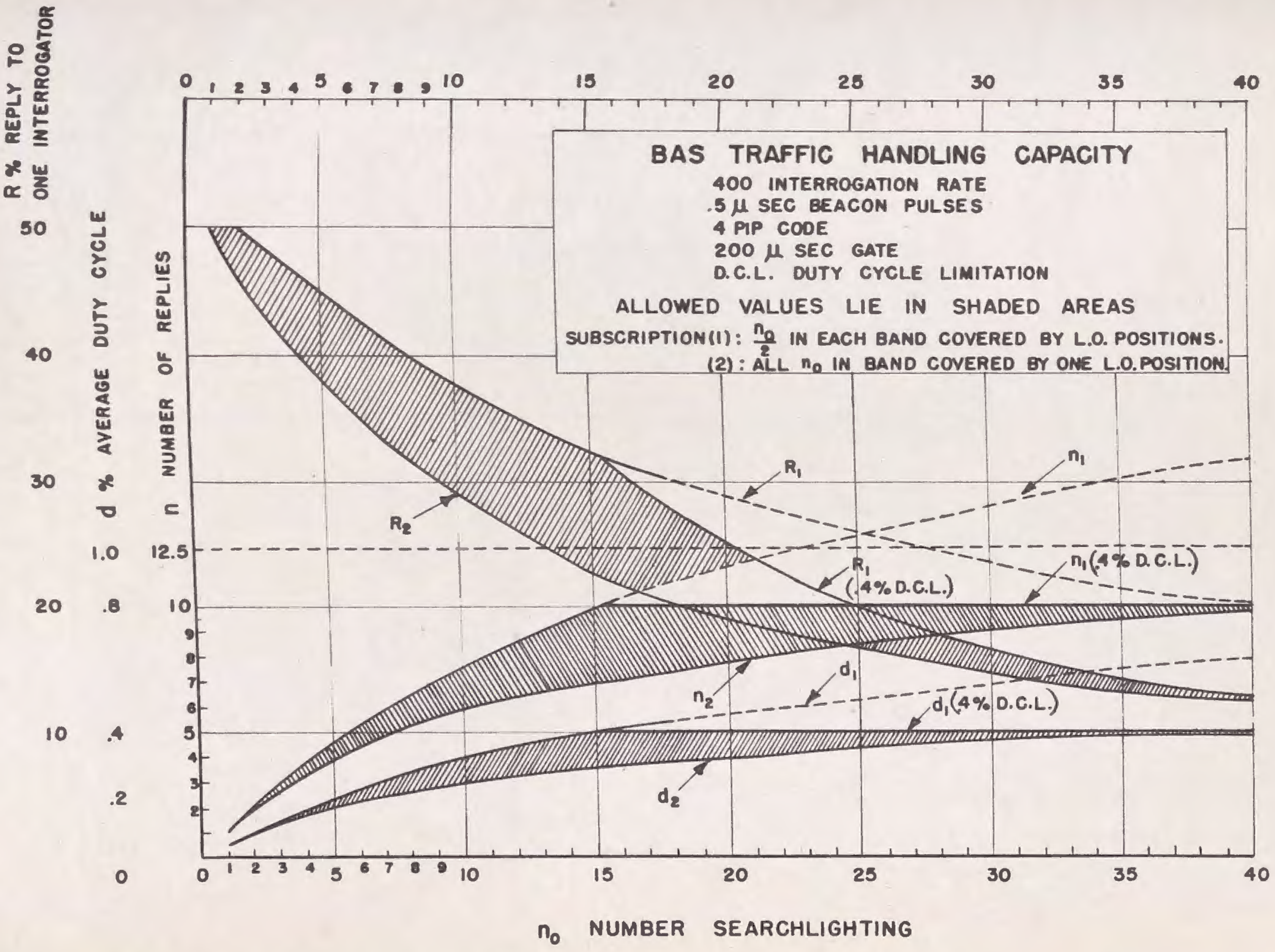

FIGURE 2

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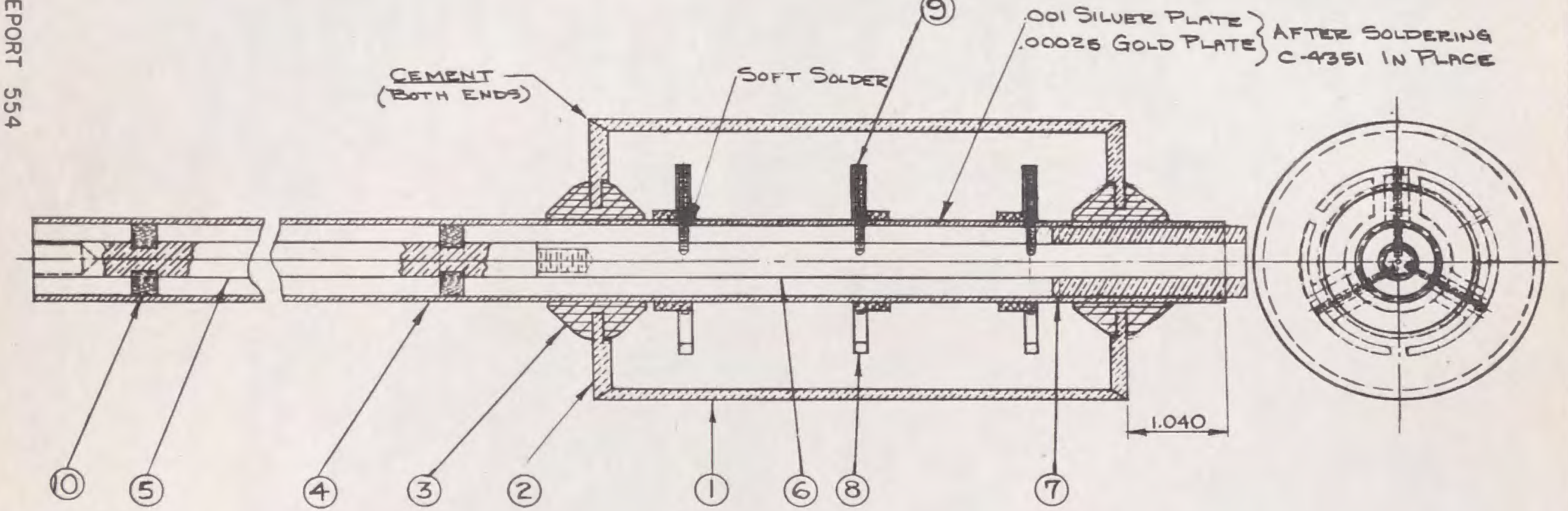

FIGURE 3

TOLERANCES ON MACHINING DIMENSIONS UNLESS OTHERWISE STATED:
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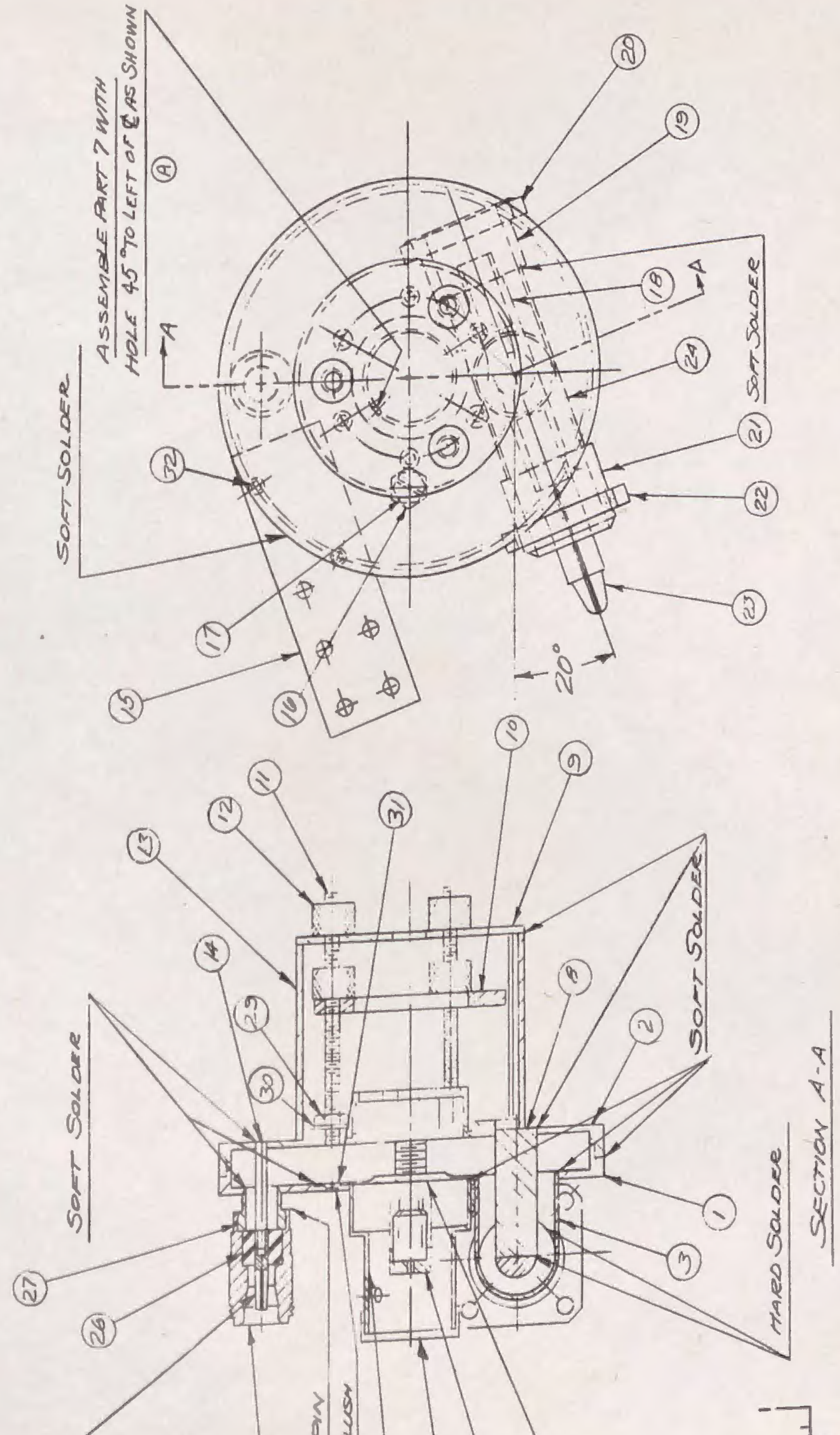
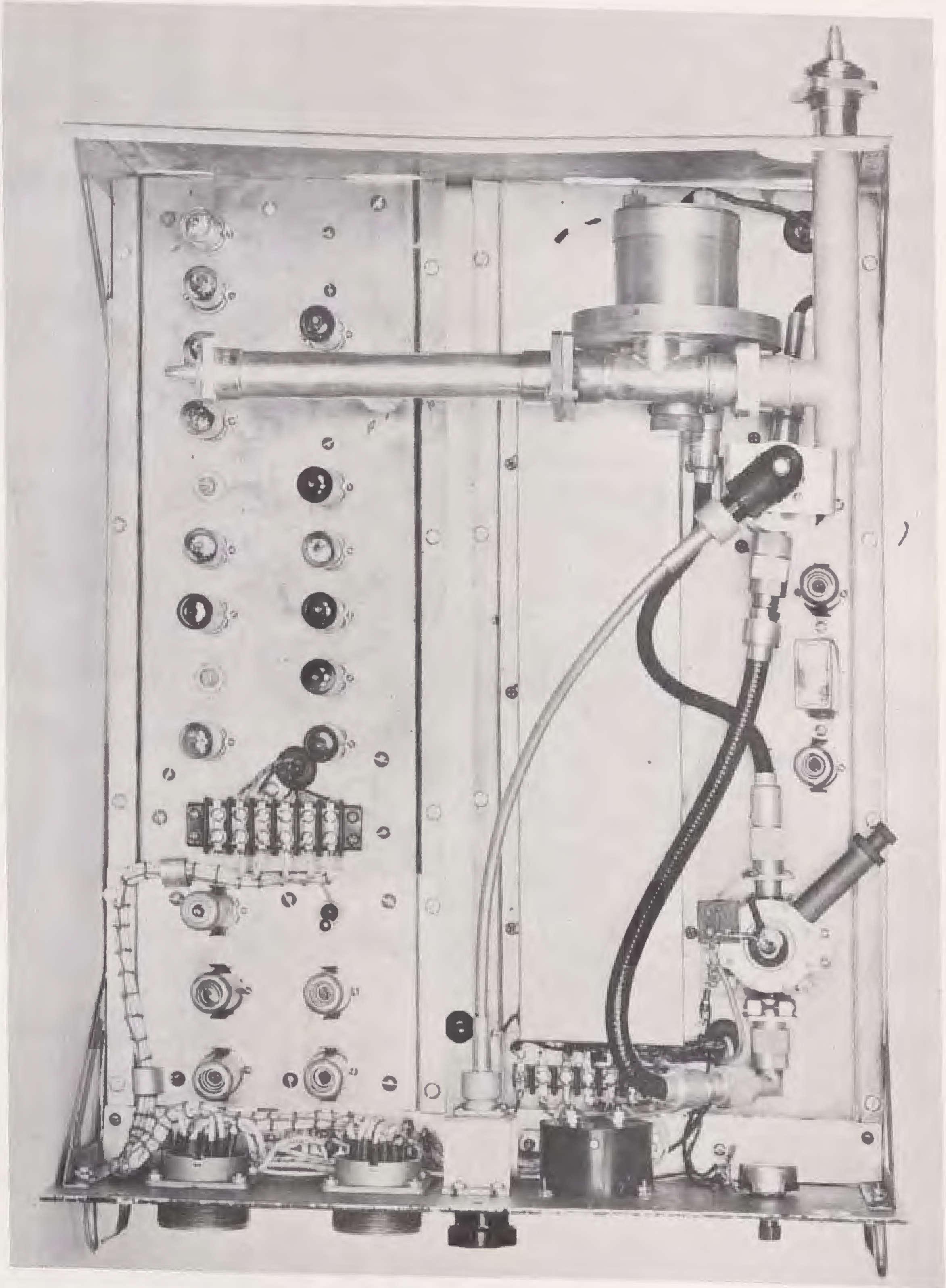
BAS ANTENNA IN AT-II
FIGURE 4



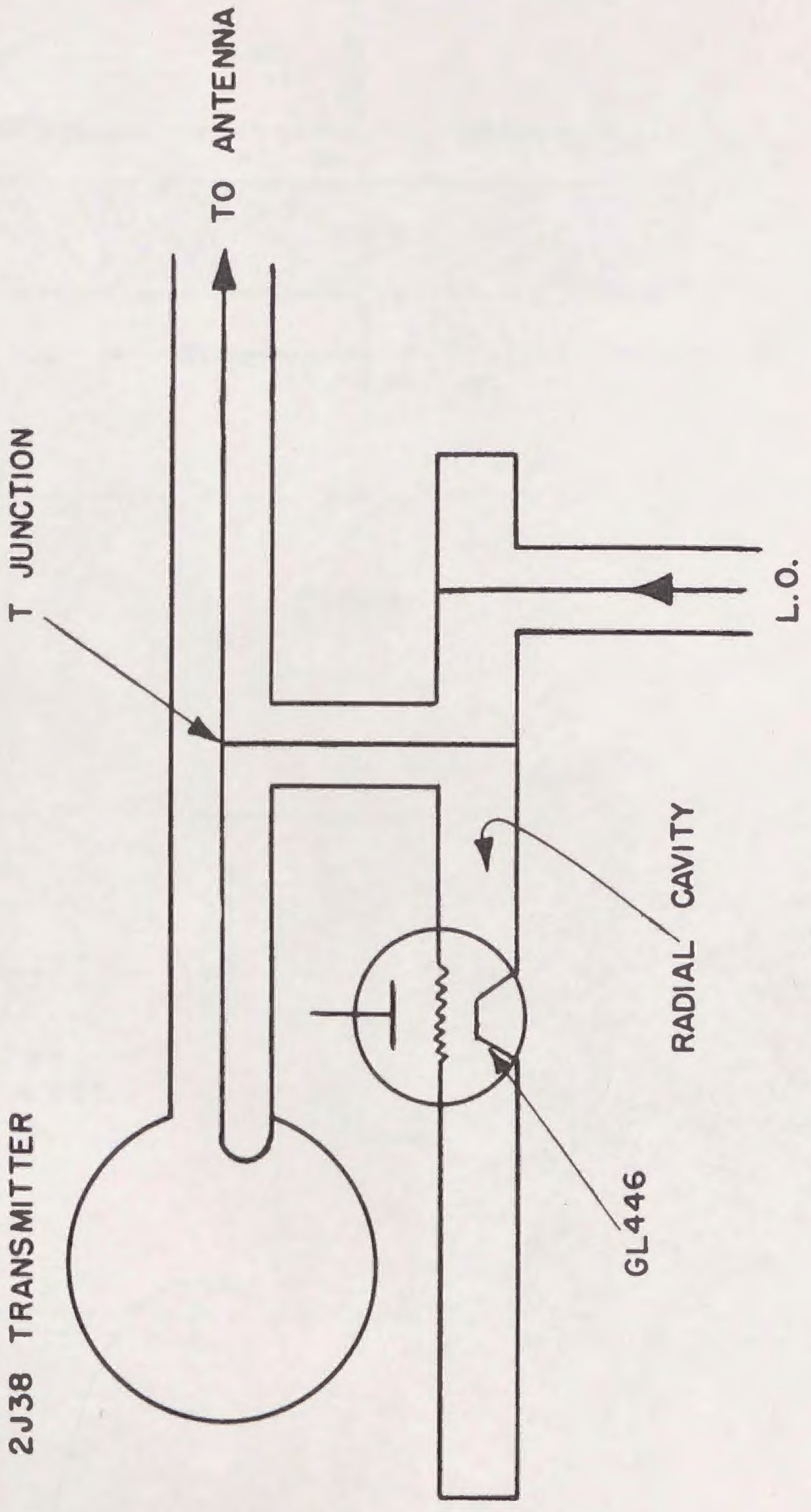
RADIAL CAVITY

FIGURE 5



BAS MODULATOR AND HV POWER SUPPLY-TOP

FIGURE 6



BAS DUPLEXER-MIXER

FIG. 7

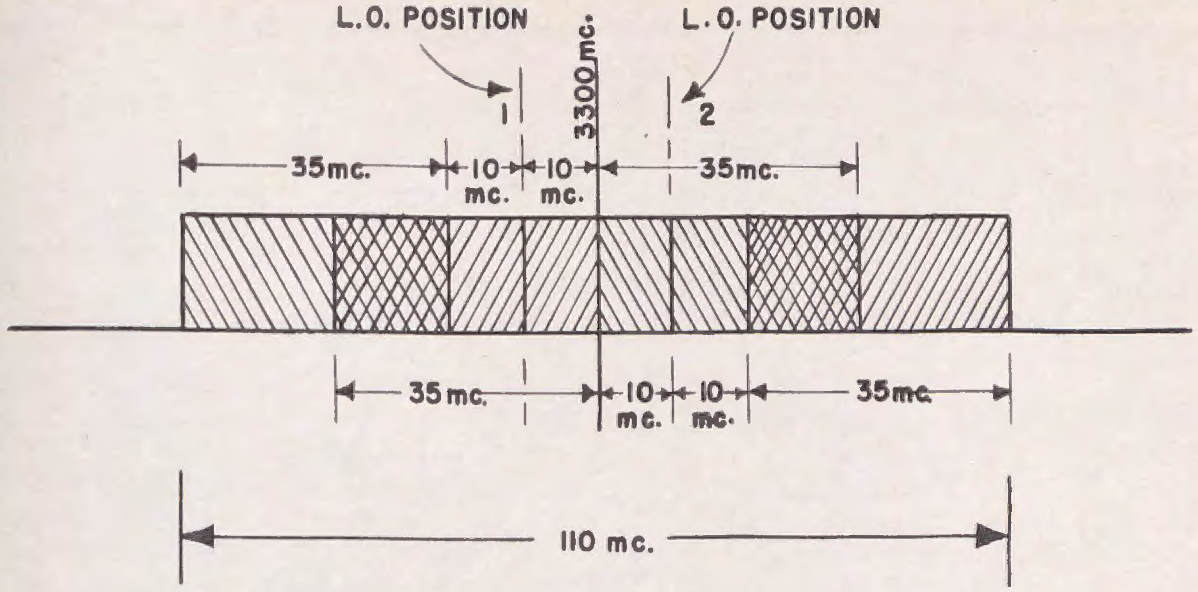


FIG. 8

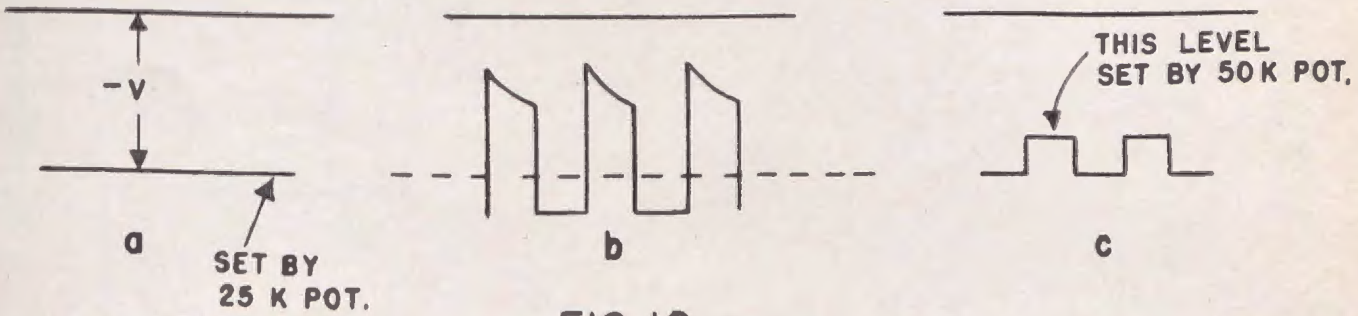


FIG. 10

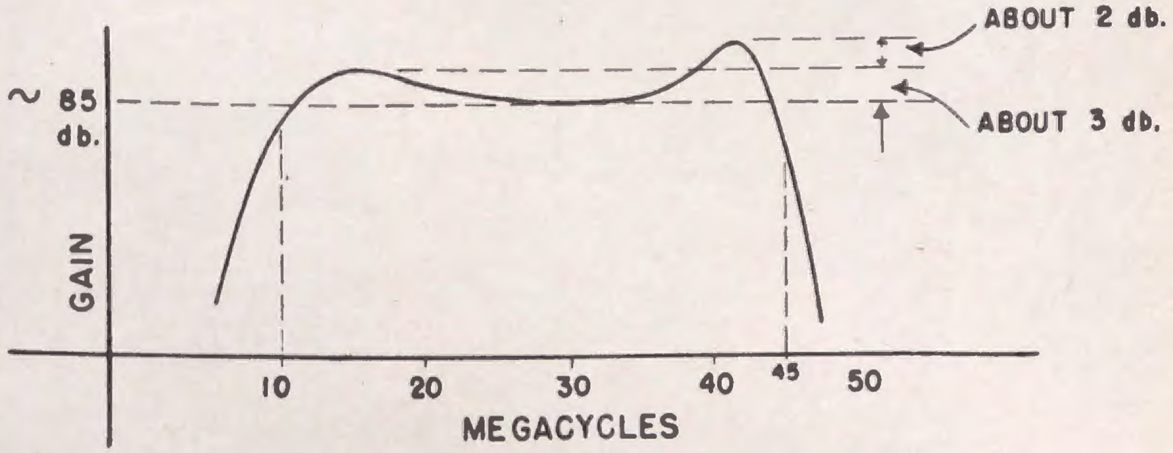


FIG. 12

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FIGURE 9

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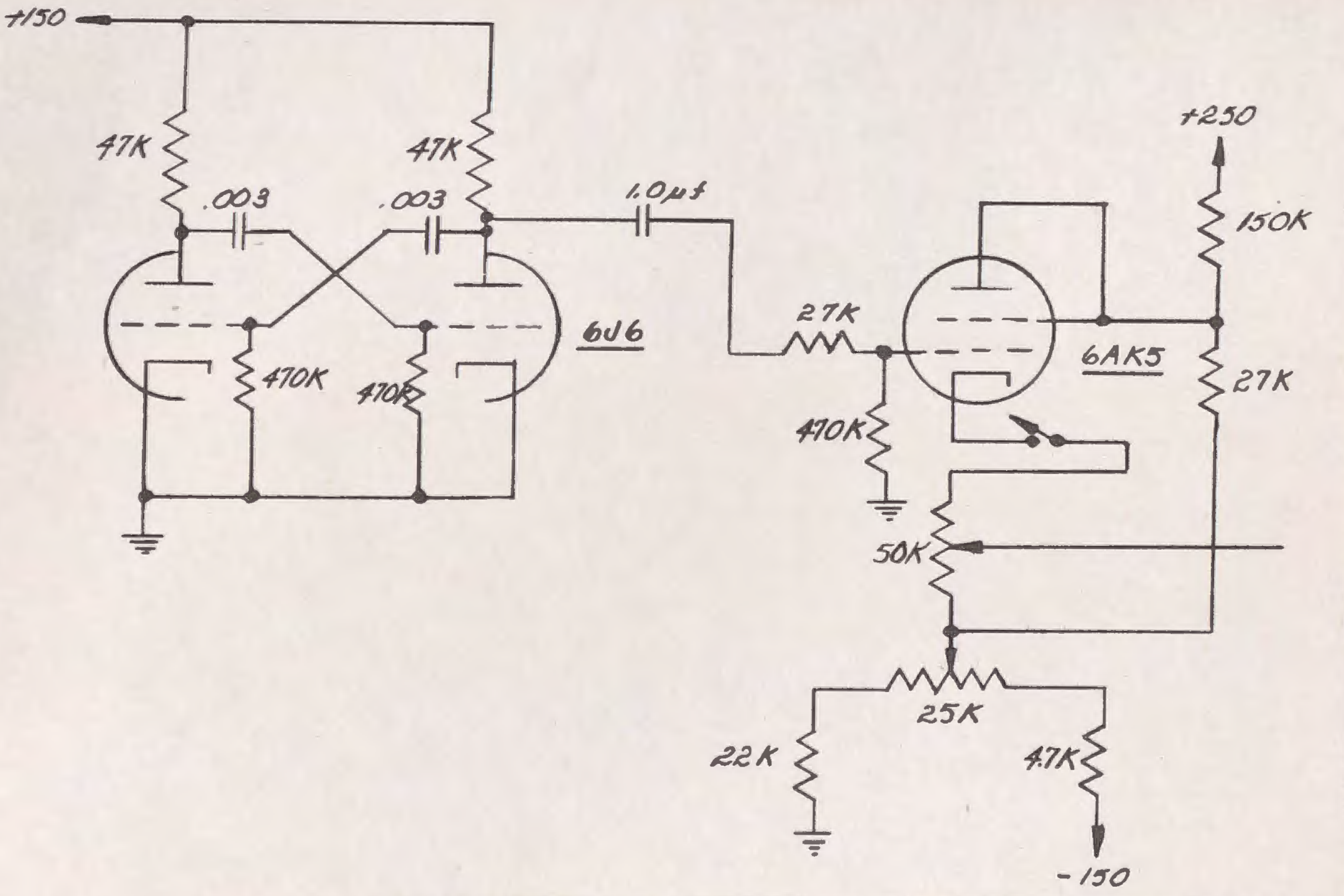

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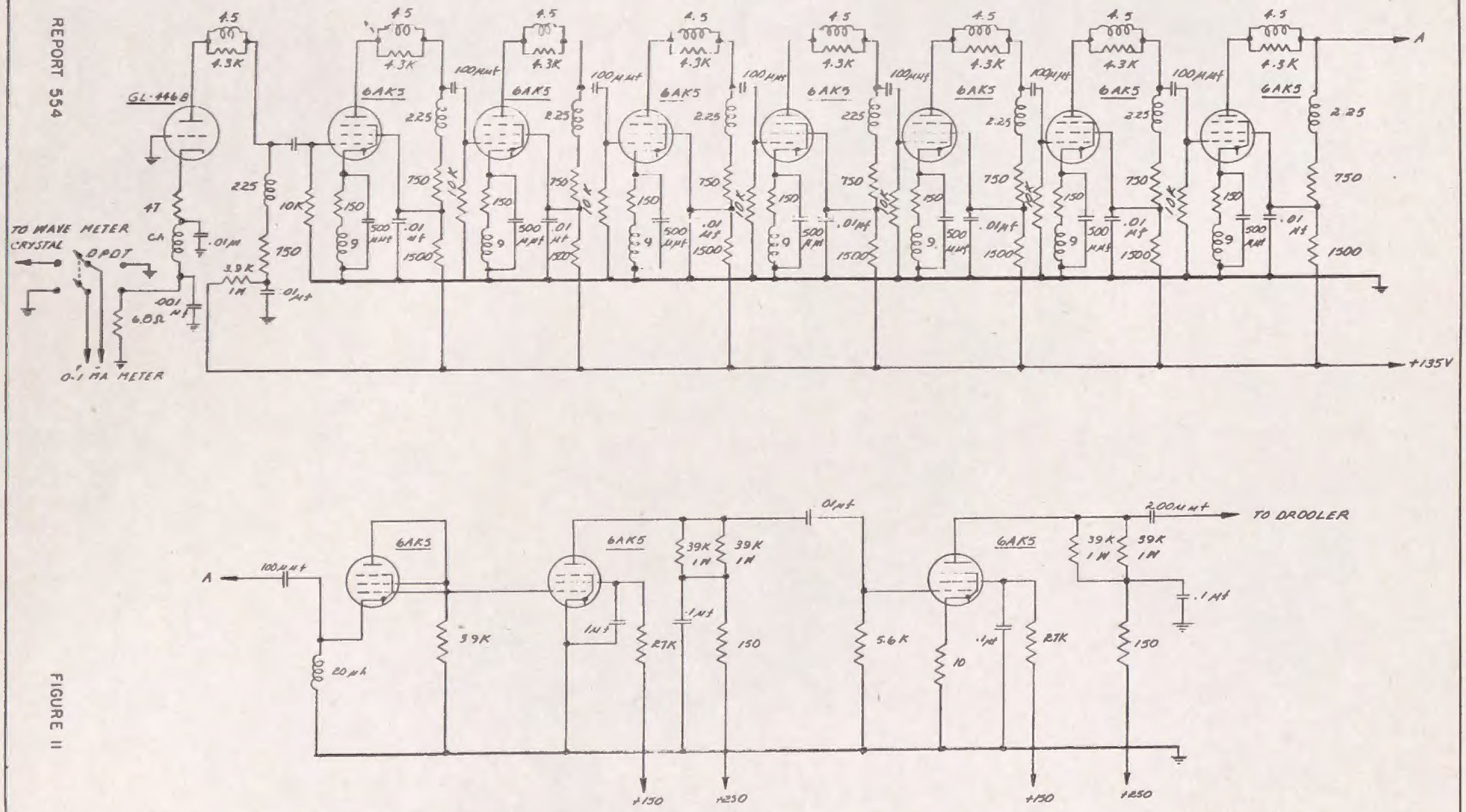

FIGURE 11

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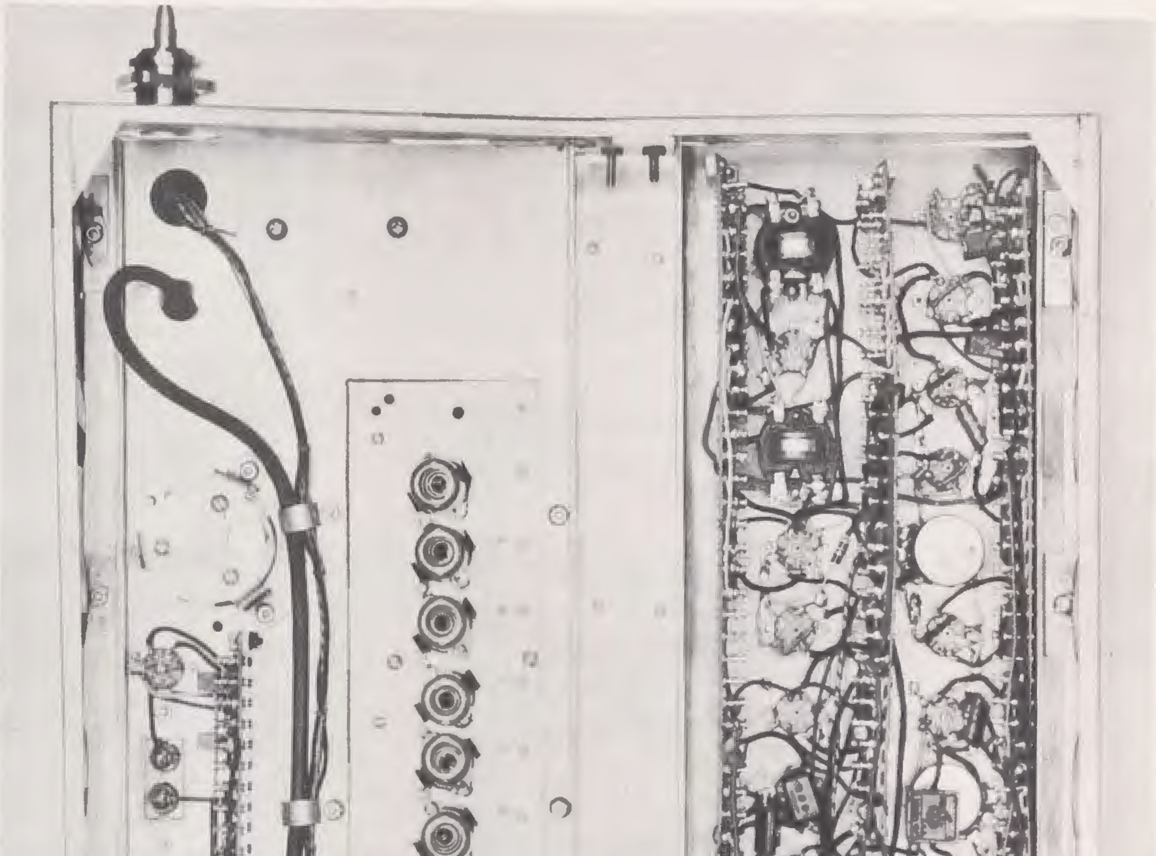
TITLE: BAS SWITCHED RECEIVER

FILE 41 DWG. NO. A-6475-C



BAS MODULATOR AND HV POWER SUPPLY—BOTTOM

FIGURE 13

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FIGURE 14

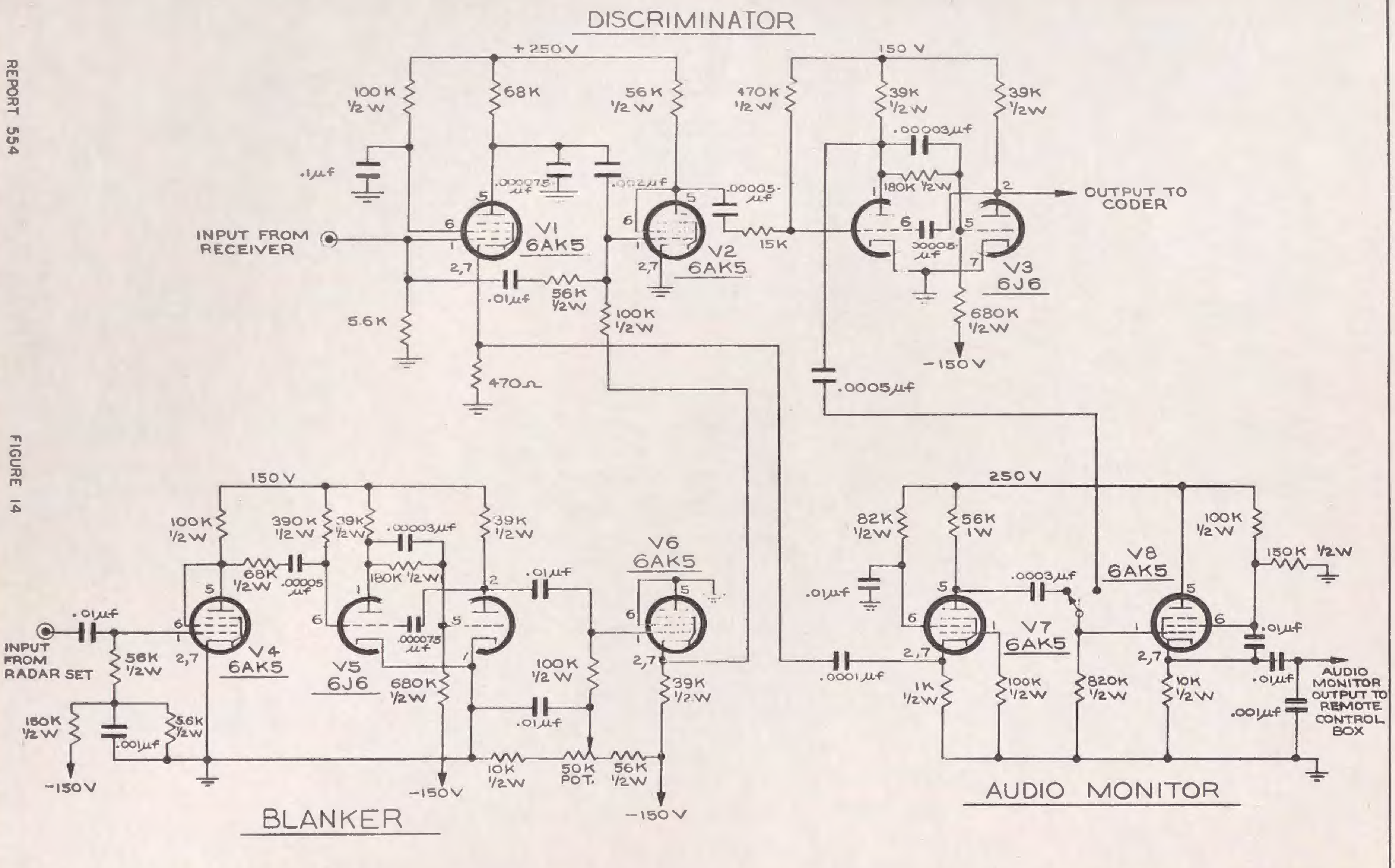

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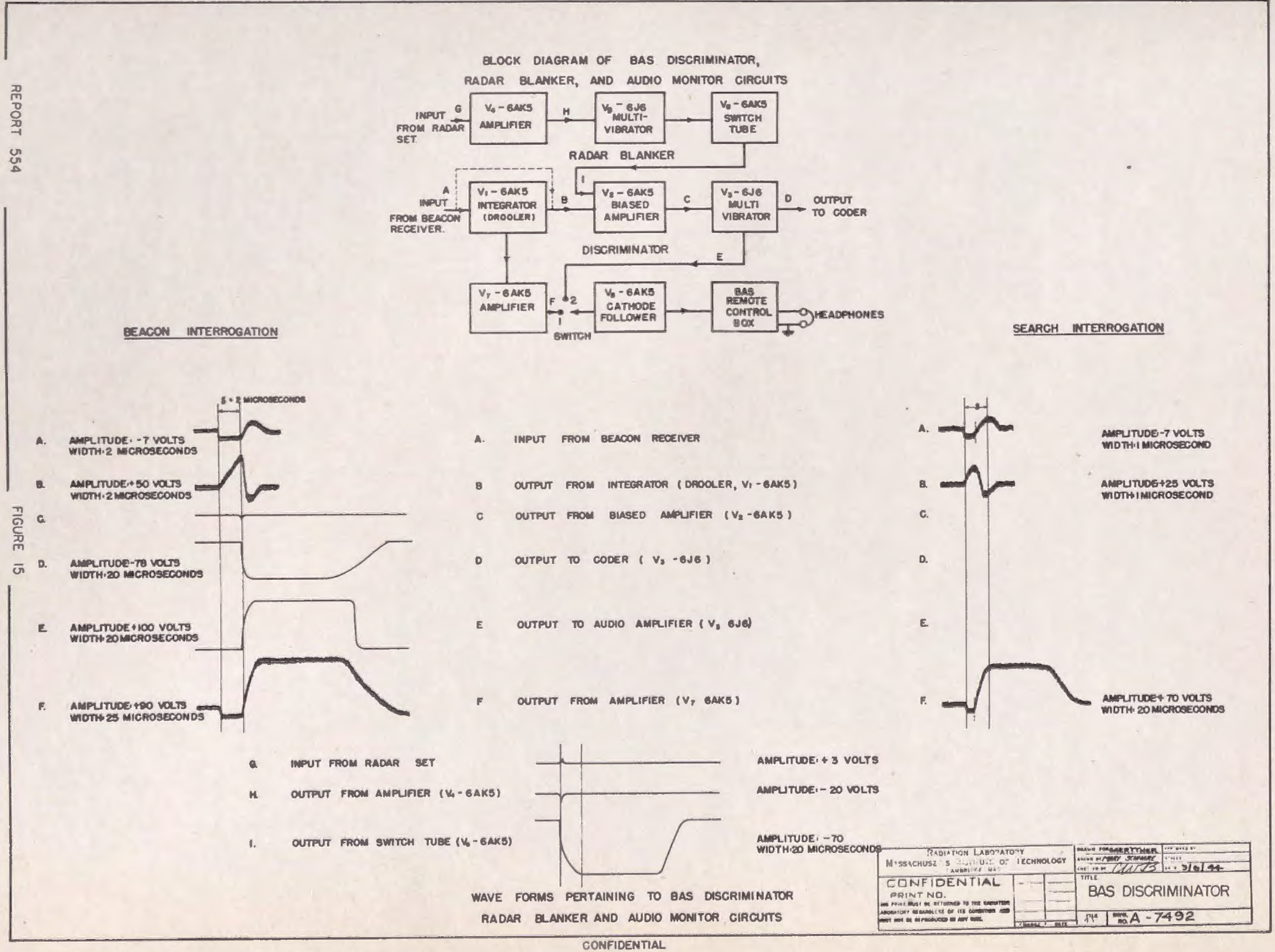
FIGURE 15



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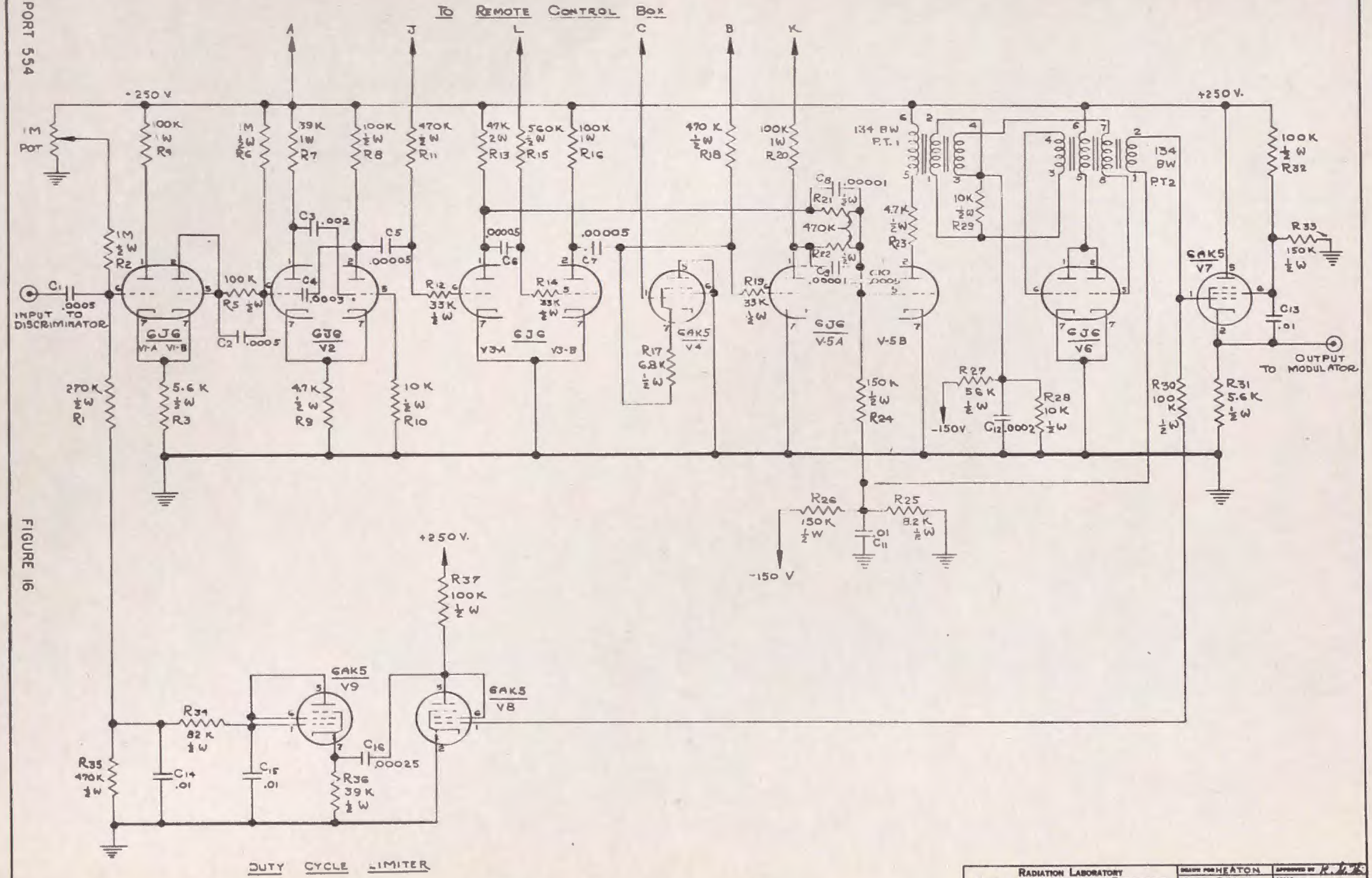

FIGURE 16

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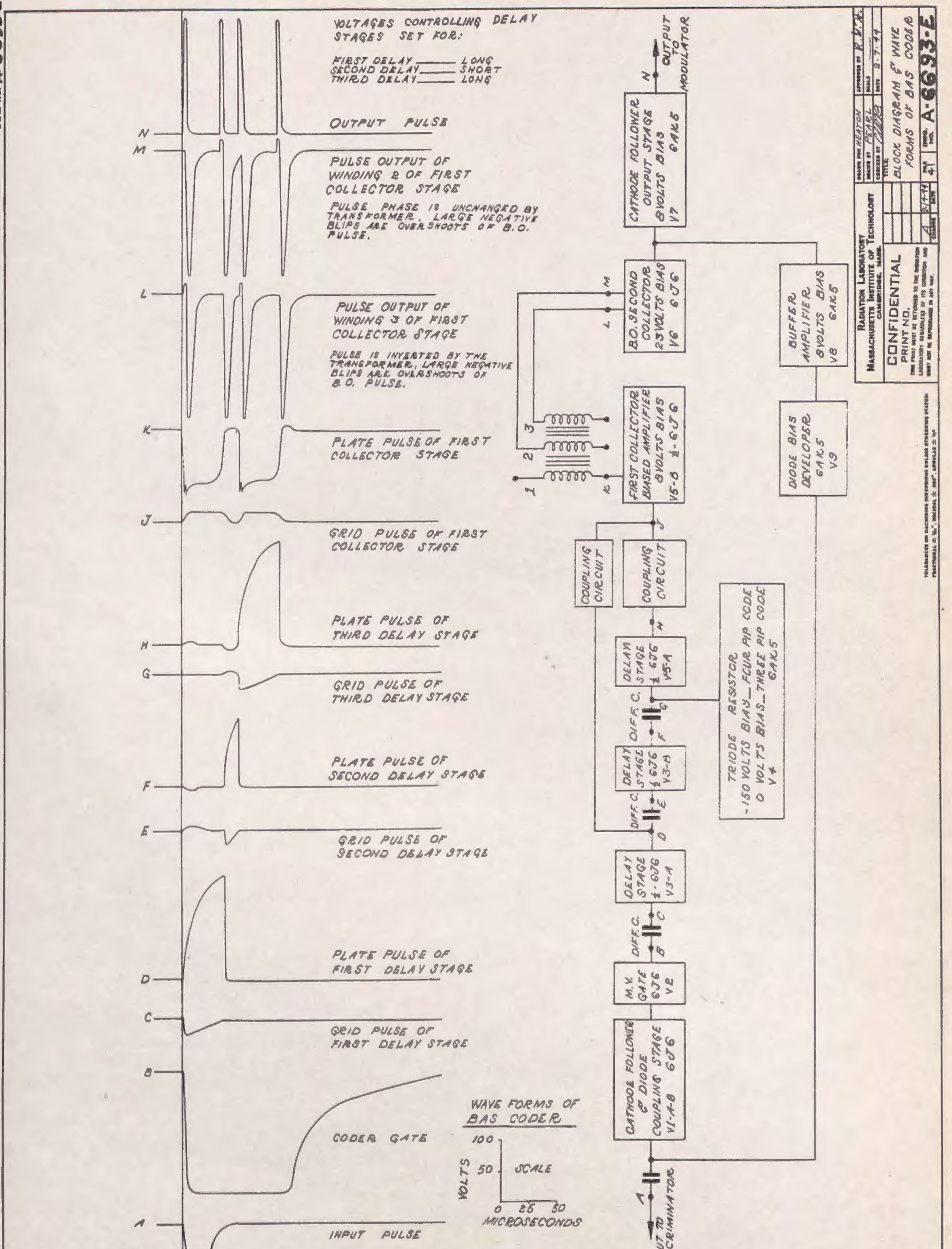
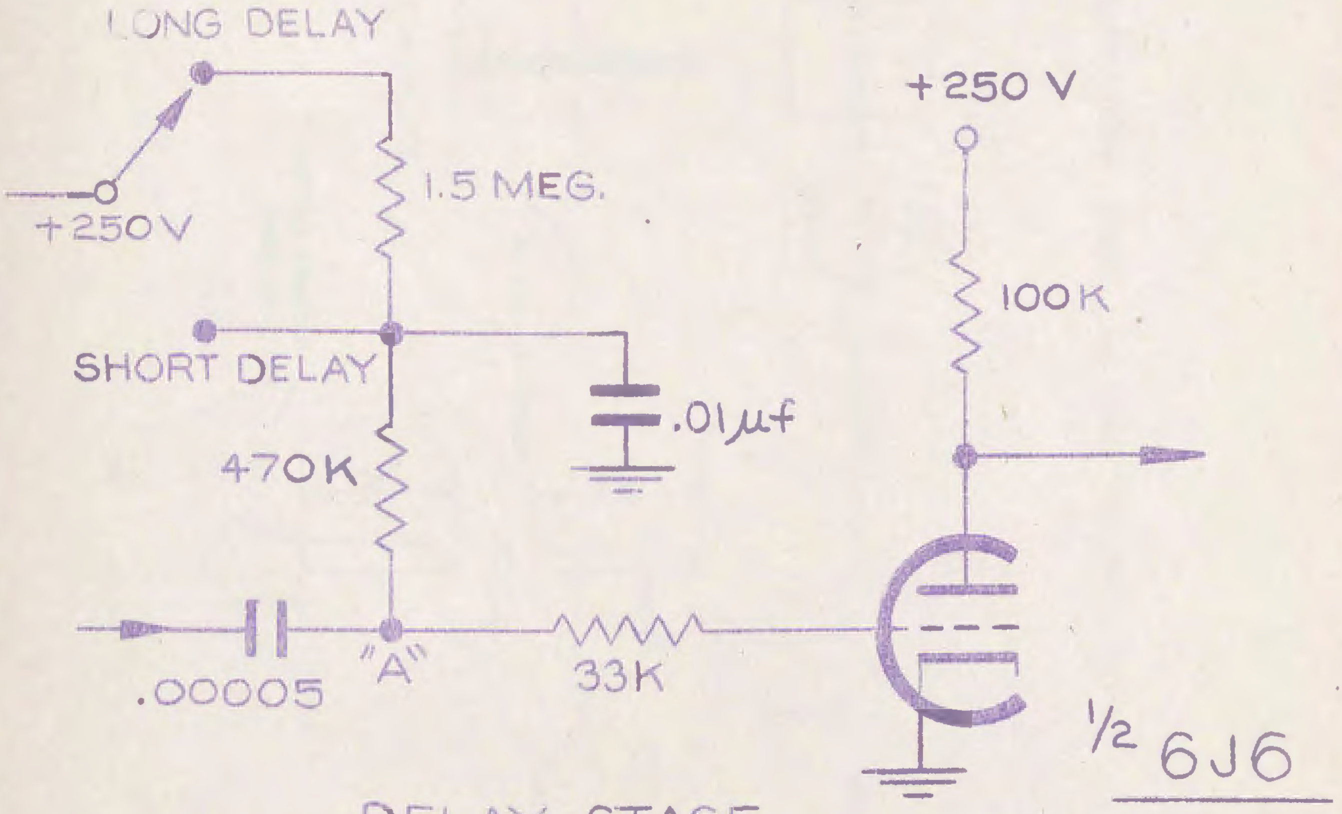
CONFIDENTIAL PRINT NO. This print must be returned to the Radiation Laboratory regardless of its condition and must not be reproduced in any way.	TITLE: BAB CODER & DUTY CYCLE LIMITER	
	41	DWG. NO. A-6693-A

TOLERANCES ON MACHINING DIMENSIONS UNLESS OTHERWISE STATED: FRACTIONAL ± 1/64", DECIMAL ± .005", ANGULAR ± ½°



REPORT 554

FIGURE 17



DELAY STAGE

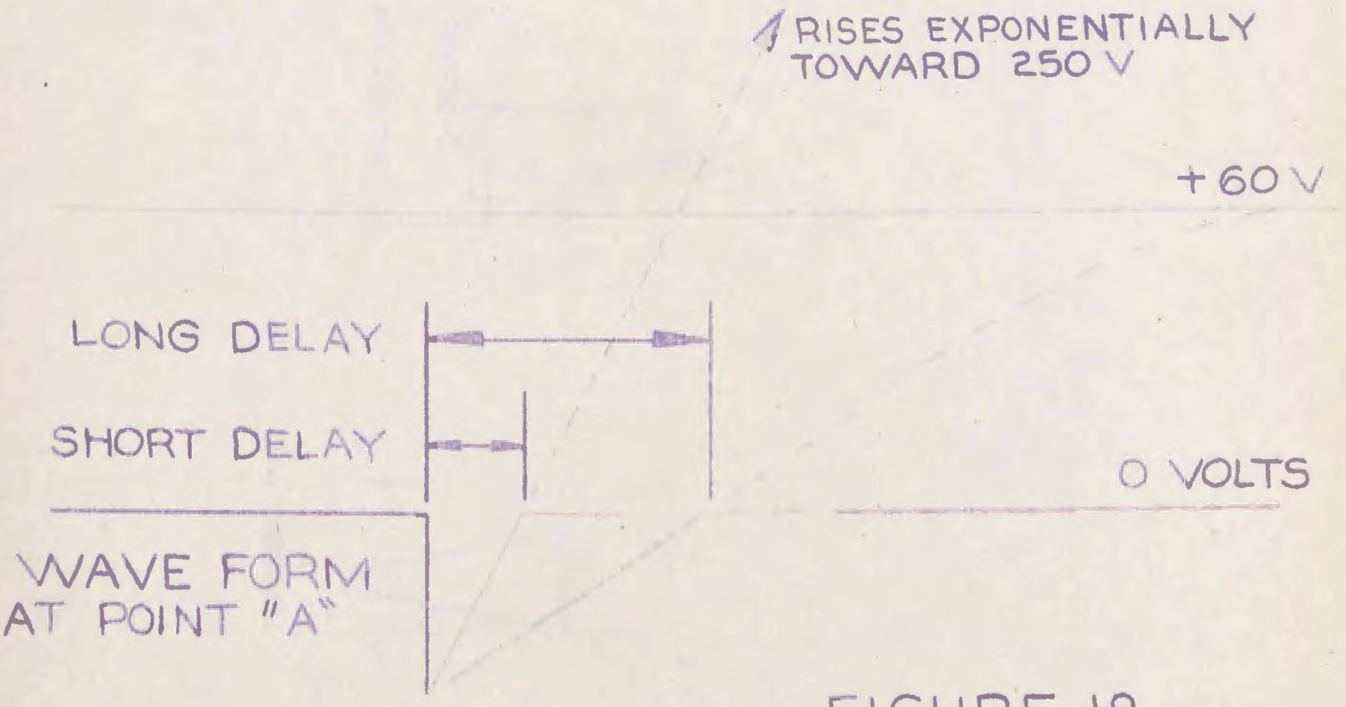
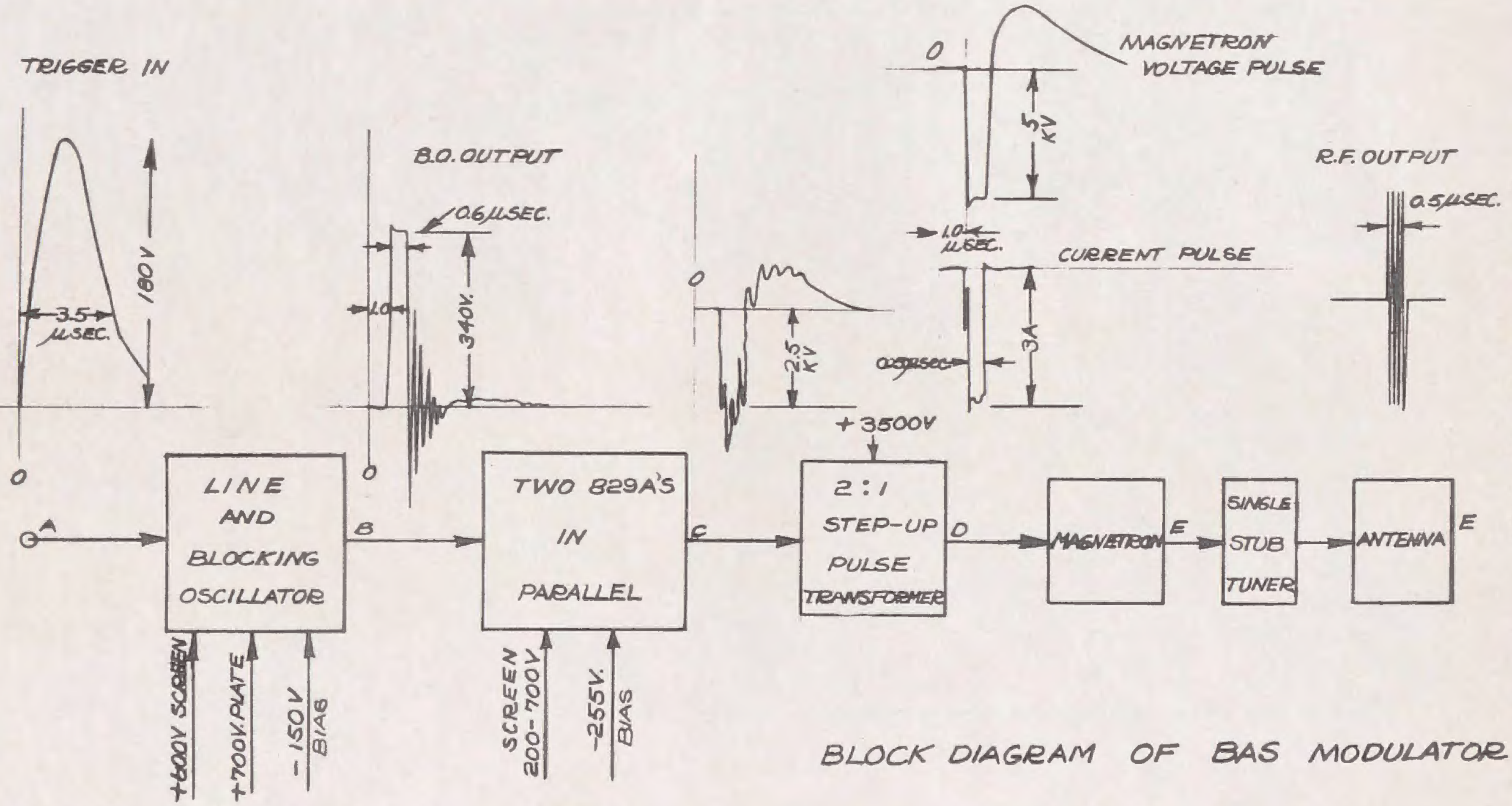


FIGURE 18



BLOCK DIAGRAM OF BAS MODULATOR

FIGURE 19

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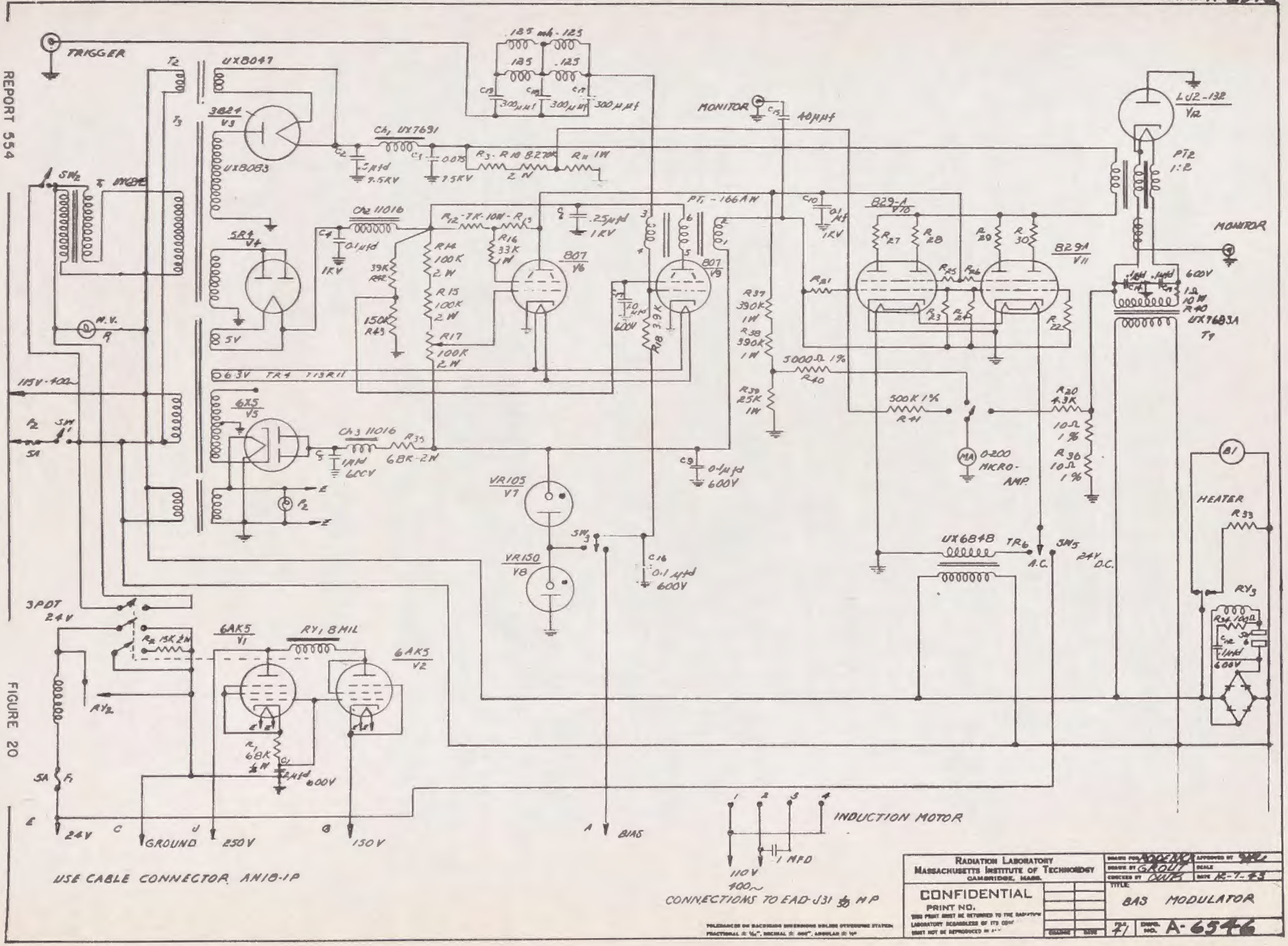
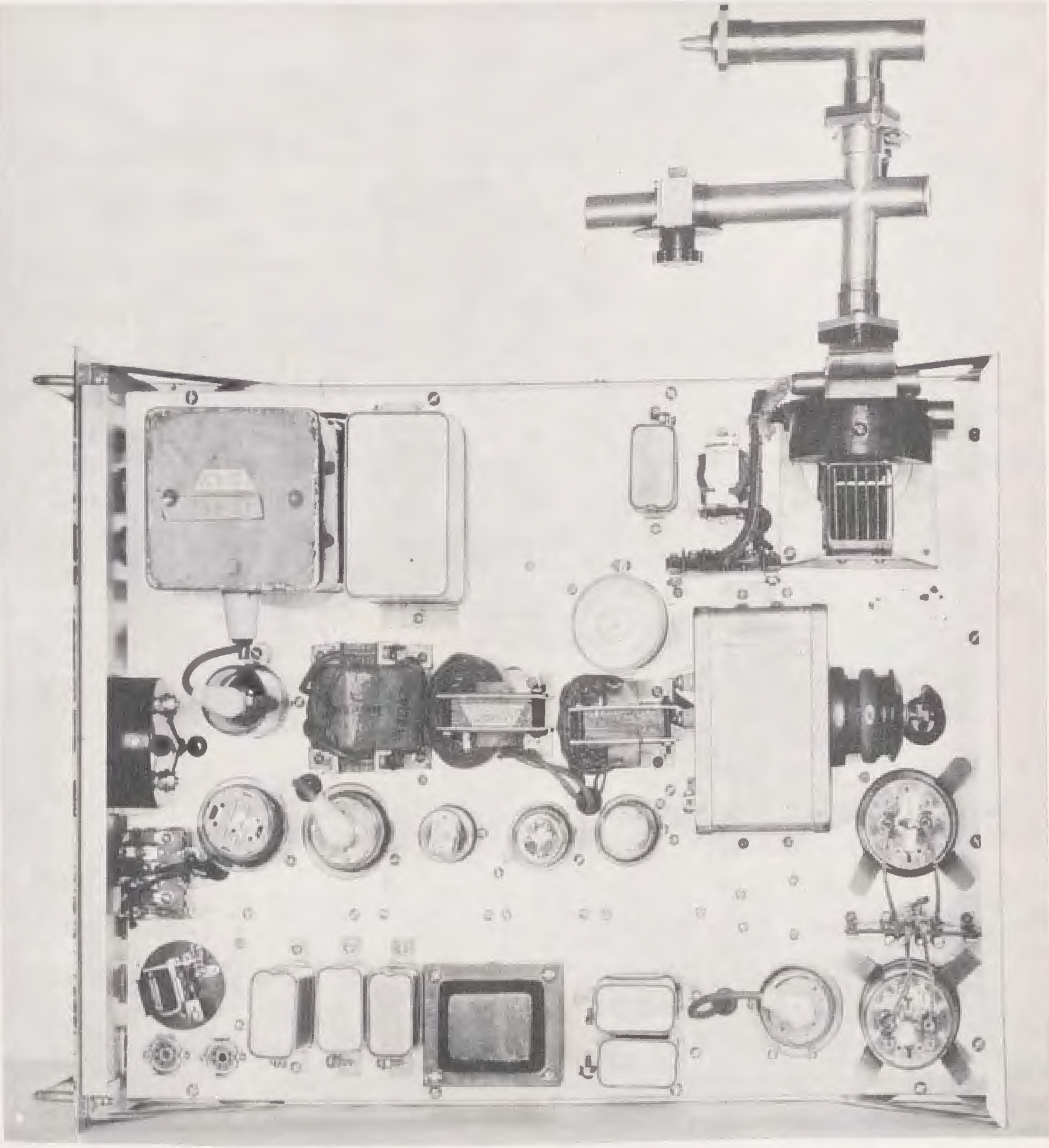

DWG. NO. A-6546
TRIGGER
UX8047
3B24
V3
UX8083
Ch1 UX7631
5R4
V4
H.V.
115V-400~
6X5
V5
Ch3 11016
6.3V
VR105
V7
VR150
V8
807
V6
807
V9
PT1 - 166AW
MONITOR
40μμf
829-A
V10
829A
V11
LU2-132
V12
PT2
1:2
MONITOR
UX7683A
T7
500K 1%
R41
0-200
MICRO-
AMP.
UX6848
A.C.
24V
D.C.
HEATER
R33
RY3
3PDT
24V
6AK5
V1
RY1 8MIL
6AK5
V2
RY2
5A
E
24V
C
GROUND
J
250V
B
150V
A
BIAS
INDUCTION MOTOR
110V
400~
1 MFD
USE CABLE CONNECTOR AN18-1P
CONNECTIONS TO EAD-J31 ⅛ HP
RADIATION LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASS.
CONFIDENTIAL
PRINT NO.
BAS MODULATOR
A-6546

FIGURE 20



BAS RECEIVER-CODER, DISCRIMINATOR—TOP

FIGURE 21

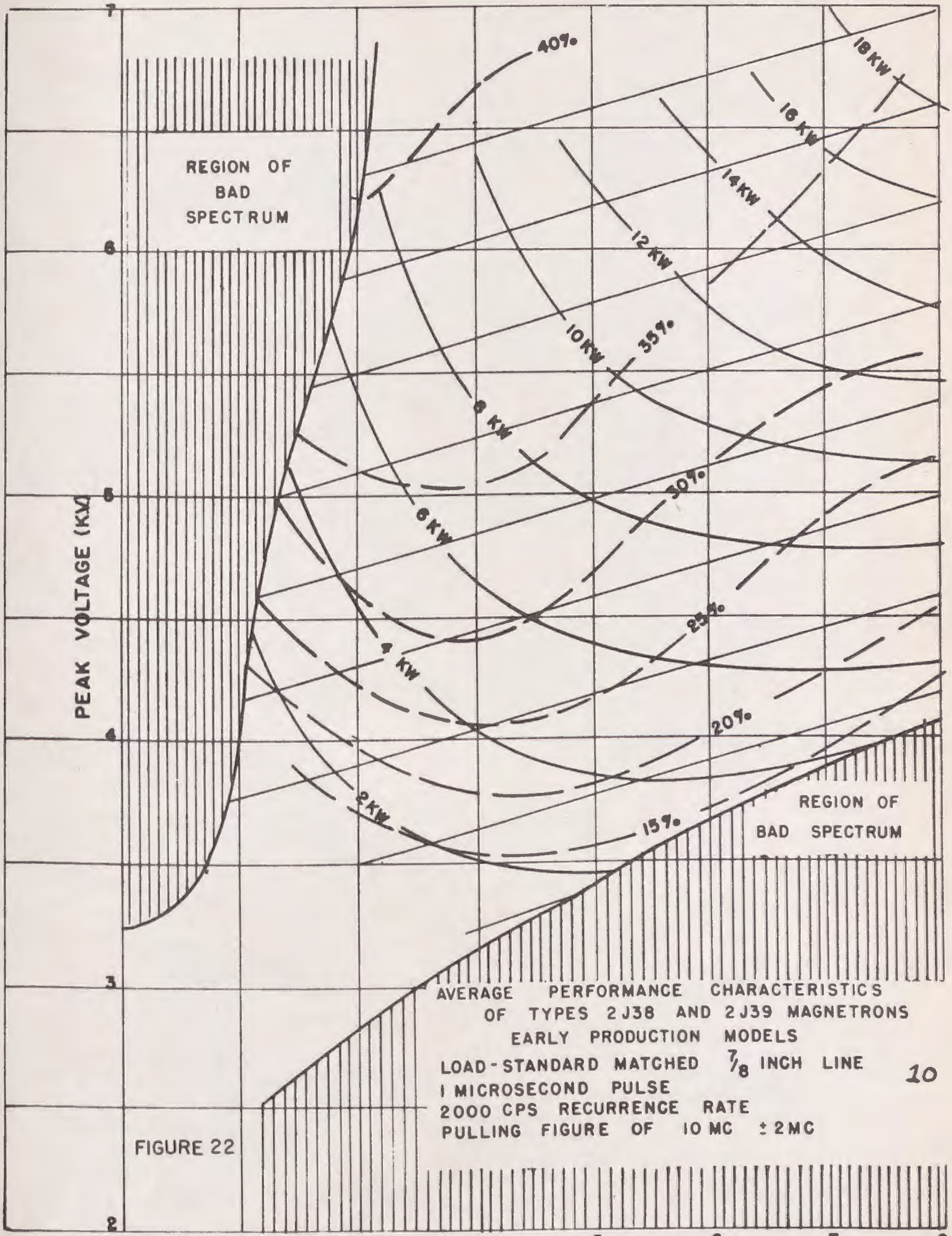
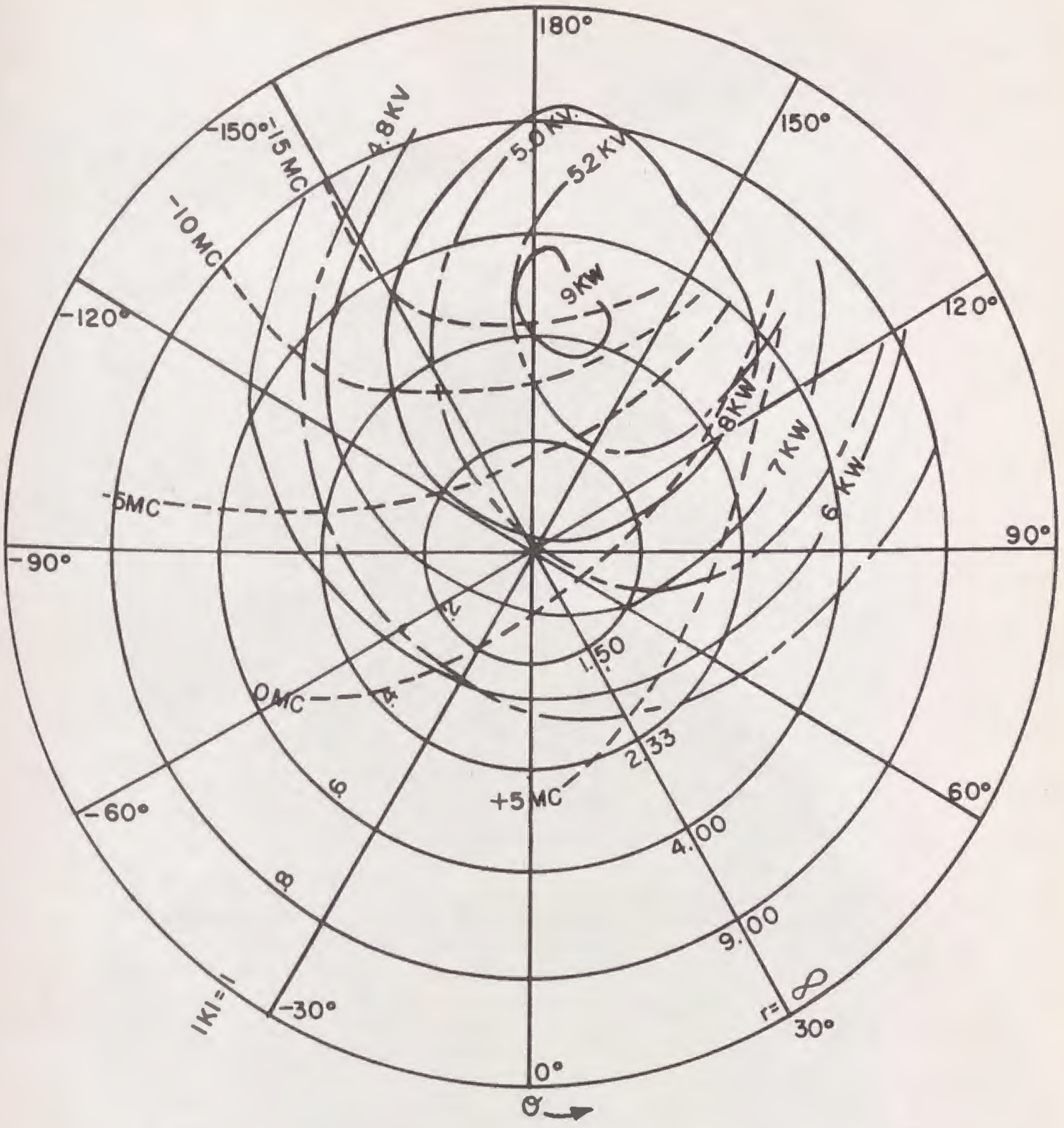

PEAK VOLTAGE (KV)
PEAK CURRENT (AMPS)
7
6
5
4
3
2
1
2
3
4
5
6
7
8
REGION OF BAD SPECTRUM
REGION OF BAD SPECTRUM
40%
35%
30%
25%
20%
15%
18 KW
16 KW
14 KW
12 KW
10 KW
8 KW
6 KW
4 KW
2 KW
AVERAGE PERFORMANCE CHARACTERISTICS
OF TYPES 2J38 AND 2J39 MAGNETRONS
EARLY PRODUCTION MODELS
LOAD-STANDARD MATCHED 7/8 INCH LINE
1 MICROSECOND PULSE
2000 CPS RECURRENCE RATE
PULLING FIGURE OF 10 MC ± 2MC
10
FIGURE 22

FIGURE 22



FPV-CONTOUR DIAGRAM
TYPES 2J38 AND 2J39 MAGNETRONS
—EARLY PRODUCTION MODELS—

OPERATING CONDITIONS
2000 CPS RECURRENCE RATE
1 MICROSECOND PULSE
MAGNETRON CURRENT 10MA (AVER)
STANDARD 7/8 INCH LINE

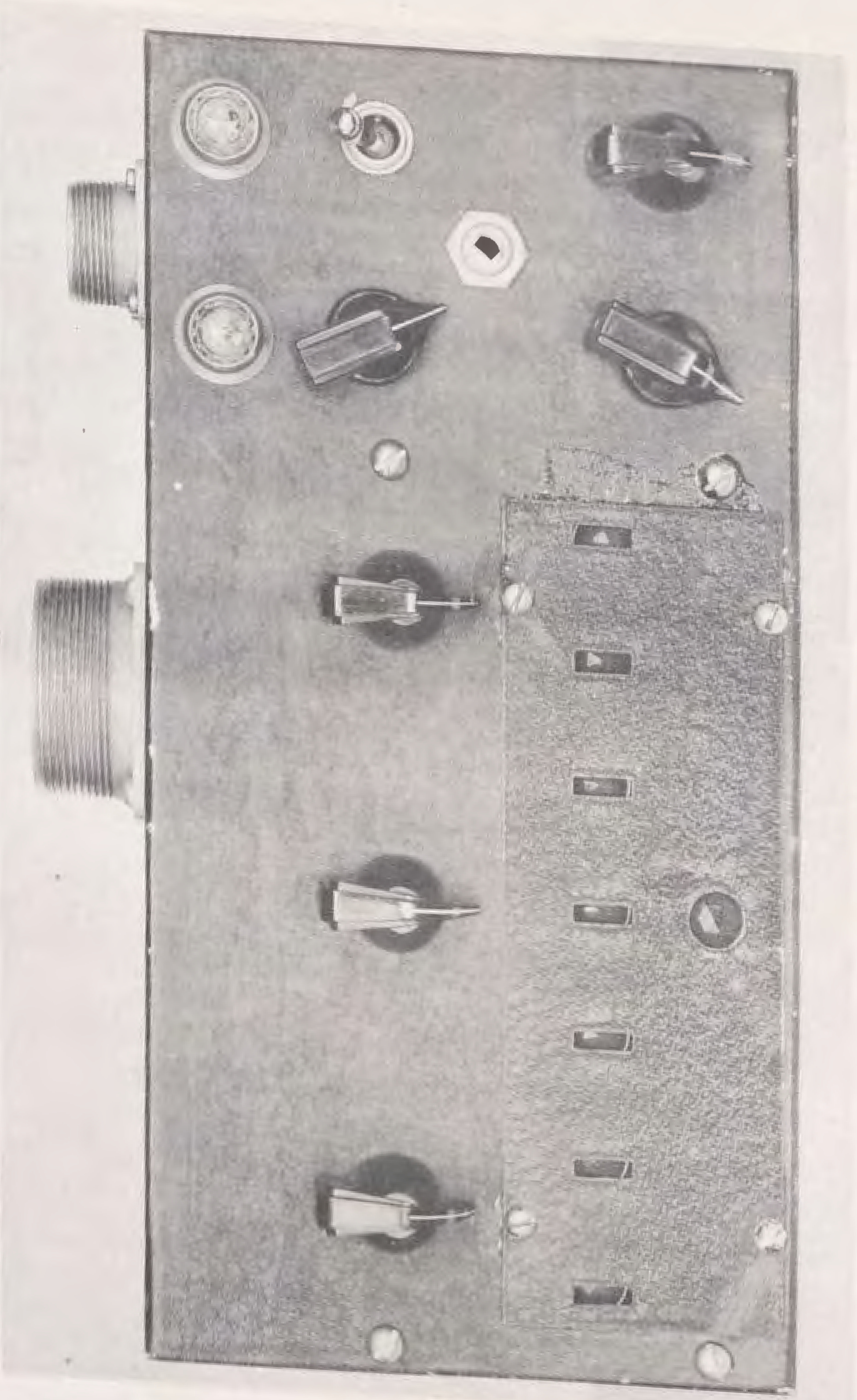
FIGURE 23

r = STANDING WAVE RATIO (VOLTAGE)
θ = DISTANCE OF STANDING WAVE MINIMUM FROM END OF CENTRAL CONDUCTOR (—TOWARD LOAD)

—— POWER CONTOURS (KILOWATTS)
- - - - FREQUENCY CONTOURS (MEGACYCLES)

—·— VOLTAGE CONTOURS (KILOVOLTS PEAK)

FIGURE 23



BAS COMPONENT - REMOTE CONTROL BOX-FRONT-
FIGURE 24